GEOMETRIC AND FUNCTIONAL KNOWLEDGE IN THE ACQUISITION OF SPATIAL LANGUAGE

by
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ABSTRACT

Considerable debate surrounds the nature of spatial categories, beginning with the observation that all languages use a limited and closed set of terms to encode object location and what appears to be a large and diverse set of object relations and configurations (Talmy, 1985). In previous work, Johannes, Landau and colleagues (Johannes, Wilson, & Landau, 2012, submitted; Landau, Johannes, Skordos, & Papafragou, under review) proposed that the structure of the conceptual categories of Containment and Support that underlie spatial language is reflected in the probabilistic use of spatial terms like *in* and *on*. The work in this thesis expands on these earlier findings by exploring the nature of the conceptual information underlying probabilistic spatial expression use and the relationship between conceptual knowledge and spatial expression use across development. The studies probe relationships between adults' and children's spatial expression use and a small set of geometric features, derived from studies of pre-linguistic spatial cognition knowledge (Hespos & Baillargeon, 2001, 2008; Hespos & Spelke, 2004, 2007), and a functional feature, Locational Control, adapted from psycholinguistic studies of *in* and *on* (Garrod, Ferrier, & Campbell, 1999). The results of three studies show that adults' and children's use of different types of spatial expressions (including *BE + in(side)/on (top)* and lexical verbs) for a large and diverse set of Containment and Support items are predicted by different combinations of geometric and functional features. Geometric features show consistent relationships to expression use across development, while Locational Control differs in its relationship to adults' and children's use of different expression types. Parents of 4- and 6-year-old participants also provided estimates of how likely they were to use different expression types to describe the same set of experimental items to their children. Including these estimates, alongside features, in models of child expression use improved the accuracy of model predictions, particularly for children's use of lexical verb expressions, which initially showed weak relationships to feature ratings. These findings are among the first to account for spatial language usage and development as a complex function of spatial (geometric and functional) knowledge and input environment and the first to systematically examine spatial encoding for such a diverse sample of items that are representative of the everyday object configurations that children and adults encounter in the world.

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Chapter 1

Natural language gives humans the unique ability to talk about objects and their locations and relations in space. All languages have a system of terms for denoting objects and a system of terms dedicated to the expression of spatial relationships between objects (Talmy, 1983). This second system generally takes the form of a limited, closed class set of terms (Talmy, 1985; Landau & Jackendoff, 1993), and it is these limited terms – their meaning, acquisition, and interaction with developing spatial and linguistic knowledge – that are the critical focus of this dissertation.

In the presented work, I uncover relationships between aspects (features) of spatial configurations between objects and the systematic patterns of language that speakers use to encode these configurations. Specifically, I ask whether spatial expression use is tied to different kinds of spatial knowledge: how do geometric and functional features of relations conspire to influence the use of particular spatial terms? After demonstrating that mature spatial language use across a diverse set of spatial relation items is indeed responsive to differences in both geometric and functional features, I investigate factors underlying the development of the spatial language system: how does a child's spatial knowledge, language environment (i.e., parent input), and developing lexicon, together, function to shape the trajectory of her spatial language acquisition? Based on previous work (Johannes, Wilson, & Landau, 2013, forthcoming), reviewed in detail below, I hypothesize that mature (adult) and developing (child) language users will show differences in the types of spatial expressions that they use across different relations, and are especially likely to differ in their use of lexical verb constructions (e.g., *attach, connect, hang*). This research is an opportunity to further explore the locus of these differences: asking, for example, whether and how developing spatial language is shaped by factors like spatial knowledge and the language-learning environment, more generally.

The quest to understand spatial language categorization – the relationship between systematic language use and underlying semantic or conceptual knowledge – has engaged researchers in every subfield of the Cognitive Sciences, including developmental psychology (Baillargeon, 1995; Hespos & Baillargeon, 2001, 2008; Hespos & Spelke, 2004; Casasola, 2005; Casasola et al., 2003, *inter alia*), computer science/AI (Herskovits, 1986; Regier et al., 2013), typological linguistics (Levinson et al., 2003; Bowerman & Pedersen, 1992 including anthropological field studies, such as Levinson & Wilkins, 2006; Ameka & Levinson, 2007), and cognitive psychology (Carlson et al., 2006; Carlson-Radvansky et al., 1999; Hayward & Tarr, 1995, Regier & Carlson, 2001). However, the diverse perspectives adopted in these fields have failed to converge on a consistent or satisfactory account of the meanings of spatial terms like English *in* and *on*, and have all but ignored the role of other types of spatial expressions, such as lexical verbs within the spatial language system. This dissertation aims to unite many of these disparate perspectives to provide a clear account of both the structure of the conceptual (or semantic) space that underlies spatial language use and the mapping between this structure and the use of multiple types of spatial expressions in mature and developing speakers of English.

1.0 Background

1.0.1 Spatial language and spatial categories

The world around us is filled with countless numbers of objects and, in keeping with this, human language has developed a large open class set of terms for labeling objects and encoding their identity on the basis of fine-grained differences in properties like shape and function (Landau & Jackendoff, 1993). The large set of objects in the world gives rise to an even greater number of potential configurations and relations between two or more objects. However, our language system depends on a small closed class set of terms to encode this relational information. Thus, encoding spatial relational information through language requires speakers and learners to somehow abstract over fine-grained differences among object configurations to systematically map a small set of linguistic terms to relations. Understanding how speakers encode spatial relations with a limited inventory of spatial terms requires jointly addressing two questions:

1. How can language reflect distinctions among the myriad spatial relations that hold between objects?
2. Assuming language does encode distinctions among relations, where do these distinctions originate?

These two questions are highly related and germane to the study of spatial meaning: establishing whether and how a small set of terms encodes many different relations places constraints on the content and form of the meanings of these terms, while hypotheses about the meanings underlying spatial encoding lead to predictions about what kinds of spatial information might be reflected in language. One goal of this work is to understand the ways in which language systematically reflects differences among relations – whether, for example, membership in the categories delineated by spatial expressions is uniform (all or none) or graded – as well as the types of information that speakers are sensitive to in their use of different spatial expressions.

The first question – how a particular spatial expression categorizes a set of spatial relation exemplars – deals with the nature of spatial expression use: do speakers use an expression uniformly over a set of relations, or is spatial language use probabilistic, with some expression-relation mappings more likely than others? The question is often left implicit in the kinds of experimental and anthropological (i.e., cross-linguistic) work on spatial language use that is reviewed in **Section 1.1**. More commonly, this mapping question is the focus of computational approaches to spatial language categorization. Some of these approaches are agnostic about the conceptual knowledge that speakers rely on for categorizing relations. The goal of such approaches is to find some systematic grouping of spatial relation exemplars through language, without necessarily justifying the conceptual similarity among exemplars. I review these approaches in **Section 1.1.1**, noting that they are necessarily descriptive insofar as they do not provide independent reasons for linguistic groupings, leaving the basis of conceptual similarity to be inferred from groupings. Other approaches, reviewed in **Section 1.1.2**, aim to predict spatial language categories on the basis of hypothesized sets of features of spatial relations, predicting which spatial exemplars should receive the same description based on whether they share features or not. This feature-based work moves towards a more explanatory account of spatial language use, and serves as a jumping off point for the proposed research. However, recent proposals for feature-based models of spatial language provide little justification of the particular features used to model spatial categorization and why speakers would apply features in e.g., a binary way when categorizing spatial relations through language.

Section 1.2 reviews recent work from our lab that moves towards the goal of jointly addressing the nature of both spatial meanings and spatial mappings. Cross-linguistic research from Landau et al. (submitted), reviewed in **Section 1.2.1**, proposes a preliminary set of conceptual distinctions, which may be reflected by spatial language use, and measures the fine-grained usage patterns of spatial expressions to determine whether these conceptual categories are delineated on the basis of differences in the rates of use of individual expressions. Work from Johannes et al. (2013, in prep), discussed in **Section 1.2.2**, builds on the design of Landau et al. to explore interactions among the acquisition of different types of spatial expressions – prepositions-based and lexical verb-based – in the linguistic articulation of different conceptual distinctions, an idea that features prominently in the proposed dissertation work.

The second question concerns the origin of the structure underlying spatial language categorization. Previous theoretical and experimental work provides a number of explicit proposals for the nature of the conceptual information encoded by spatial terms, focusing mainly on English spatial prepositions like *in, on, above, below,* etc. as case studies. These proposals come in a number of forms, reviewed in turn in **Section 1.3.1**: those which prioritize *geometric* information as the basis for spatial meaning, drawing on notions such as contact and enclosure, and the representation of objects through points, lines, volumes, and axes; those which prioritize *functional* information – the functional purpose of the spatial relation between objects; and what I'll term *hybrid* proposals, which combine geometric and functional considerations. In **Sections 1.3.2** and **1.3.3**, I bring pre-linguistic and cross-linguistic research to bear on the question of candidate meanings for spatial terms.

The work in this thesis focuses on the spatial language used to encode Containment and Support relations, traditionally labeled topological relations (Piaget & Inhelder, 1956, Bowerman, 1996a, 1996b; Talmy, 1977). In English, attention has fallen on the spatial prepositions *in* and *on*, which are taken as the primary vehicles for expressing Containment and Support relations, respectively (Bowerman, 1996; Feist, 2000; Gentner & Bowerman, 2009; Herskovits, 1986, *inter alia*). These terms are of particular interest in the Cognitive Sciences because while they are among the earliest words acquired by children (Johnston & Slobin, 1979), with meanings that appear deceptively simple, these terms have broad and sometimes nuanced uses, making *in* and *on* notoriously resistant to formal definition (Feist, 2000; Herskovits, 1986; Garrod et al., 1999, *i.a.*). However, the work itself will also highlight a lesser-studied class of spatial expressions: lexical verb constructions like *connected to* and *hanging from*, which until recently (see Johannes et al., 2013, in prep; Landau et al., submitted) have been ignored for languages like English (but see Ameka & Levinson, 2007 for discussion of verbs in the spatial systems of many other languages).

1.1 What is the nature of the mapping between spatial conceptual information and spatial expression use?

1.1.1 Spatial categorization without conceptual considerations

A number of accounts of spatial categorization aim to infer shared or universal conceptual structure from shared cross-linguistic patterns of spatial term use. These typological accounts, two of which I review here, choose a diverse set of languages and, for each language, identify an inventory of relevant “basic” spatial (locative) expressions – the most basic answer to the question “Where is (object) X?” (see Levinson et al., 2003; Levinson & Wilkins, 2006 for more details on the basic locative construction). If English were in the set, for example, this inventory would be comprised of expressions with a copular verb and some mono-morphemic spatial preposition (*above, below, beside, near, in, on, under, etc.*). Spatial descriptions are then collected from speakers of each language and aggregated. In the two cases I discuss, Levinson et al. (2003) and Regier et al. (2013), this aggregate measure is calculated by determining the modal expression – the single expression that the majority of speakers chose – for a particular spatial relation scene. A correspondence is then calculated between patterns of expression use across languages. For Levinson et al. (2003), this correspondence measure compares how often a particular spatial expression in each language is used for pairs of spatial scenes and then compares language-specific groupings of scenes by expressions to one another. The resulting picture of categorization for Levinson et al. takes the form of an attractor space, scaled to two dimensions via Multi-dimensional Scaling. Their scaled space shows a few strong clusters, each with a handful of scenes that are consistently encoded with the same (language-specific) modal expression across languages, along with a large set of isolated cases – scenes that are not consistently encoded across languages and, therefore, are not part of any cluster. Based on these analyses, Levinson suggests that adpositions across languages do not directly reflect universal (or, constant) conceptual primitives or features of spatial relations, but rather reflect a semantic space that is shaped by a small set of attractor points, which may be common to all languages.

For Regier et al. (2013), correspondences of expression use across languages takes the form of a semantic map, or network of connections between scenes, based on expression use. Scenes are organized and connected in such a way that if speakers of one language use the same expression for scene A and scene C in the map, they are also predicted to use that expression for scene B (which connects A to C in the map). The ultimate goal of the semantic map approach is to account for these kinds of implicational relationships in spatial language use for any language using the same map with the minimal number of connections. Regier et al. infer a map of connections using a subset of their collected language data and report that the set of connected nodes (scenes) in the map also correctly predicts the connections among the subset of data that was used for training. From this, they suggest that spatial language systems tend to be organized with implicational relationships among the extensions of expressions and that these relationships reflect a similarity space among spatial scenes that may be common across languages.

Both of these accounts are successful in modeling spatial language categories across multiple diverse languages. That is, they systematically account for the spatial language data collected for a number of unrelated languages, suggesting that the semantic space underlying spatial language systems is structured through attractor points (Levinson et al., 2003) or implicational relationships governing the extension of spatial terms (Regier et al., 2013). Both approaches, however, work out to be descriptive accounts of spatial language use: adequately describing the patterns of language use that generated the models but not providing insight into why these patterns exist. Specifically, and despite how the authors frame their respective results, these accounts do not generalize beyond the particular scenes used (scenes in the TRPS, Bowerman & Pedersen, 1992) to provide an independent basis for the structure or constraints that underlie the spatial language patterns they model. In **Section 1.1.2**, below, I review several studies that aim to go beyond purely descriptive typological accounts of spatial language use by incorporating conceptual information, in the form of features, into models of spatial language categorization.

1.1.2 Spatial categorization with conceptual features

Recent approaches to spatial categorization have taken conceptual information as a starting point for modeling the use of spatial expressions within and across languages. Instead of taking the approach of studies in **Section 1.1.1**, where spatial expression choice fuels inferences about possible conceptual categories and structure, the research reviewed in this section starts with a set of (conceptual) features that might apply over many spatial scenes and aims to relate these features to patterns of spatial language use across languages.

Feist (2000) proposed a set of binary features (attributes, in her terms) that determined whether a spatial term could be used to describe a particular scene. The eight classes of features she arrived at are listed in (1). A spatial term's lexical entry consisted of a subset of these features that were weighted for importance. These weighted features functioned like a set of non-necessary preference rules (in the sense of Jackendoff, 1983): the more features, especially highly-weighted features, in the lexical entry for a spatial term that match the relation in a scene, the better that term is for encoding the scene.

(1) Different classes of spatial relational features (from Feist, 2000, p. 98)

a. Figure (object) higher than ground (object)
b. Figure higher than ground, no contact

c. Figure higher than ground, with contact

d. Ground supports figure with contact

e. Contact

f. Inclusion of figure by ground

g. Absence of inclusion of figure by ground

h. Generalized spatial term (indicates spatial relation in the absence of other attributes)

These features, on Feist's account, aggregate in different ways to account for the meanings of different spatial terms in diverse languages. Features in each set (or lexical entry) are weighted in relative importance to predict the use of these terms to encode scenes with relations that roughly map to the English terms *in, on,* and *over*. Thus, one may expect to find that certain attributes regularly co-occur in lexical entries across languages, but this need not be the case.

In more recent work, Xu and Kemp (2013) built on Feist's account of spatial meaning by expanding both the set of possible features[1] in lexical entries and examining the nature of the relationships between sets of features and the use of a particular spatial term. Xu and Kemp develop their feature set to include, in addition to Feist's attributes in (6), mechanical notions like hanging, adhesion, and attachment. The main goal of their study, however, was to determine whether spatial meanings (or use of a particular spatial term for a particular scene) could be modeled as (weighted or discrete) combinations of these arguably primitive spatial features. To this end, they compared a series of computational models that differed in

[1] Many of the features added by Xu and Kemp (2013) can, in fact, be traced to specific lexical items. For example, they add a 'hang' feature, which, presumably, makes up the core meaning of the spatial verb *hanging*.

the permitted combinations of features: whether, for example, a model could combine multiple features with or without negation (the absence of a feature) in a way that was either discrete or weighted. The models were designed to predict whether a spatial term would be used (by the majority of speakers in a language sample, as in Levinson et al., 2003) for a scene on the basis of whether the proposed set of features that made up the meaning of the spatial term were consistent with the features that were independently rated to apply to that scene. As language data, Xu and Kemp used the same set of modal expression responses that Levinson et al. (2003) discussed. They then took the same scenes and had a set of naïve participants report whether each feature in their feature set was true of the scene. As in Feist (2000), these features were modeled as binary – either applying to a given scene or not – but their combinations could be weighted in a way that made gave some feature relative importance over another. This weighting, however, did little to improve the predictions of the models, which were most accurate when combinations of features, along with their possible negations, were permitted.

The work of Feist (2000) and Xu and Kemp (2013) take us a step beyond the categorization studies of e.g., Levinson et al. (2003) and Regier et al. (2013) in understanding the kinds of conceptual information that may underlie spatial expression use across languages. These accounts are helpful in that they propose independent sets of features and then attempt to relate these features to expression use across languages. However, these approaches also face a number of theoretical and empirical shortcomings, many of which I aim to address in my proposed research. First, the features (or attributes) chosen by both Feist (2000) and Xu and Kemp (2013) are highly variable in their content, origin, and complexity, ranging from the presence or absence of “Contact” to mechanical notions like

"Adhesion", and it is unclear how (or why) a young child would come to acquire these diverse sets of spatial attributes when learning early spatial terms like *in* and *on*. The proposed work aims to account for spatial expression use in English by appealing to features of spatial relations that are grounded in pre-linguistic spatial knowledge. Additionally, like the work of Levinson et al. (2003) and Regier et al. (2013), the conclusions from these accounts are limited by data reduction. Specifically, Feist (2000) and Xu and Kemp (2013) analyze coarse-grained modal responses instead of e.g., the distribution of responses from individual subjects. Finally, both of the feature-based accounts reviewed here treat features (or attributes) as binary, either applying to a spatial scene or not. I propose that the geometric and functional information that speakers attend to when encoding spatial relations is much more nuanced, with features applying in gradable ways. This conception of a feature-based account also accords with the final observation that spatial expression use is also not an all-or-none affair: speakers often have multiple expressions at their disposal for encoding a given scene – a consideration that is notably absent from all of the reviewed work on spatial categorization, making spatial language use, itself, a gradable phenomenon. In **Section 1.3**, below, I present evidence for thinking about spatial expression use as probabilistic, with the mapping of expressions to relations as a graded profile instead of a set of discrete categories.

1.2 How are spatial expressions distributed across languages and development?

1.2.1. Fine-grained measures of spatial expression use across languages

Research from our lab, starting with Landau et al. (under review), takes steps towards jointly investigating the conceptual space that underlies spatial expression use and the mapping between expressions and this conceptual space. Landau et al. aimed to uncover structure in the underlying conceptual space through fine-grained examination of spatial language use. Specifically, we asked how sensitivity to different conceptual distinctions is reflected in speakers' spatial expression use across multiple languages.

This and subsequent work contributes two important jumping-off points for the proposed research. First, Landau et al. used a hypothesis-testing approach to establish salient points and structure within the underlying conceptual space. We collected a sample of scenes of Containment and Support relations and grouped them into a battery that would later be used to elicit spatial descriptions. The battery was divided into subtypes of Containment and Support relations, with multiple scenes selected for each subtype. These subtypes represented a broad range of cases drawn from various theoretical (Herskovits, 1986; Jackendoff, 1996) and experimental (Bowerman, 1996; Bowerman & Levinson, 1993; Bowerman & Pedersen, 1992; Casasola et al., 2003; Gentner & Bowerman, 2009; Hespos & Spelke, 2004; Levinson et al., 2003; Levinson & Wilkins, 2006, *i.a.*) accounts of spatial meaning. Approaching spatial encoding with a hypothesized set of distinct subtypes allowed us to test for reliable differences in language use based on differences in properties – both geometric, such as the distinction between tight-fitting vs. loose-fitting relationships, and mechanical, such as the difference between an object hanging from vs. sticking to another object – common to subtypes of relations, instead of on the basis of individual, highly variable, scenes.

Second, we measured the *rate* at which adult and child speakers of English and Greek used the spatial expressions *is in* (*ine mesa*, in Greek) and *is on* (*ine pano*, in Greek) to encode different subtypes of Containment and Support relations, respectively. Measuring expression use in this way revealed fine-grained differences in the way speakers encoded different subtypes of Containment and Support relations. Furthermore, the patterns of expression use (i.e., the patterns of relative differences in expression use) across subtypes were similar for speakers of both languages. Taken together, these results suggest that systematic variability in expression use within a language is revealing of structure and organization within the underlying space of Containment and Support relations. Speakers use spatial expressions at reliably different rates to encode different subtypes of Containment relations – their rate of use of expressions like *is in*, for example, distinguishes loose-fitting Containment (e.g., an apple in a bowl) from tight-fitting Containment (an egg in a carton), interlocking relations (a key in a lock), and embedded relations with negative spaces (a crack in a mug). Furthermore, the similarity of these distributional patterns suggests this organization might be common across diverse languages like English and Greek.

Landau et al. along with related work by Johannes et al., reviewed below, provides preliminary evidence for systematic structure in the conceptual domains of Containment and Support relations, revealed by fine-grained patterns of expression use. However, this work does not directly inform us about the structuring principles of the space: what abstract features or properties of these subtypes allow speakers to encode relations with the same expression (*is in*/*ine mesa*; *is on*/*ine pano*), but make some subtypes more likely to be encoded by these expressions than others? Related to this, the subtypes we chose were derived from a theoretical model of possible distinctions among Containment and Support relations. That is, the set of subtypes examined were not derived by identifying and manipulating properties or features of spatial relations but rather were developed by selecting cases that varied on any number of dimensions. In my thesis research, I also use fine-grained measurements of expression use to test hypothesized structure in Containment and Support categories. The hypothesized structure of my sample differs from that of Landau et al. in that it is based on variation in a small number of features instead of differences across a series of distinct subtypes.

1.2.2. Lexical verb expressions in the acquisition of spatial language

Johannes et al. (2013, in prep) used a similar approach to Landau et al. with the goal of understanding English-speaking children's acquisition of an articulated profile of spatial expression. We used the same subtypes (though, with different scenes for each subtype) as the previous study and uncovered patterns of *is in*/*on* use over Containment and Support relations that were similar to those reported by Landau et al. In this study, however, we placed special emphasis on differences in children and adults' use of both preposition-based *is in*/*on* and lexical verb based expressions like *hang from* and *stick to*, and children's joint acquisition of these two forms of spatial language.

We observed that children and adults used lexical verb expressions at dramatically different rates in their descriptions of both Containment and Support relations: adults often described a scene like the one in Figure 5c (below) with a lexical verb expression such as *the shirts are hanging from the line*, while children almost always used an expression with a copular verb such as *the shirts are on the line*. In total, one quarter of adults' Containment descriptions and half of their Support descriptions featured lexical verb expressions, while young (four-year-old) children used lexical verbs in only a handful of descriptions overall.

For adults, the profile of lexical verb use was complementary to their profiles of *is in*/*on* use, which was not the case for children. When children did not use *is in*/*on* in their descriptions, they typically turned to other prepositions paired with the copular verb (*is* *above/below/beside/near/in the middle of, etc.)*, suggesting that their responses were not simply an overwhelming preference for *is in/on*, but rather a *dis*preference for lexical verbs in spatial expressions. This dispreference, and the relative uses of lexical verbs and *is in/on* expressions changed over development, with 6-year-olds using lexical verbs at rates that were intermediate between 4-year-olds and adults. Thus, the adult profile of spatial language use features a balance of preposition-based (mainly *is in/on*) and lexical verb-based expressions that reflects distinctions among subtypes of Containment and Support relations. Children, however, are still developing this balance and do not show the fully-articulated profile of expression use that adults have, despite learning expressions like *is in/on* relatively early in the course of language acquisition (Johnston & Slobin, 1979).

The work presented in Johannes et al. highlights a developing 'balance' between early- acquired expressions, like *is in/on*, and later-acquired lexical verb expressions in the profile of spatial language use for Containment and Support. However, this work stops short of accounting for why the meanings of some of these forms are more accessible to children than others. That is, what kinds of knowledge (linguistic, conceptual, pragmatic, etc.) do children need to have in order to recruit lexical verbs to encode spatial relations? The proposed studies acknowledge the joint development of articulated profiles of preposition-based expressions like *is in/on* and lexical verb expressions. However, in the proposed work I move on to address the additional roles of conceptual knowledge and linguistic experience (that is, the linguistic input environment). I first ask to what extent children's knowledge of geometric and functional features, measured through a feature-rating task, is predictive of their use of prepositional and lexical verb expressions. Given this relationship between child feature knowledge and language use, I then turn to the question of the degree to which the quality of parental input for an individual child mediates her use of different spatial expressions.

1.3 What kind of conceptual information are speakers sensitive to in their use of spatial expressions?

1.3.1 Geometry and function in the meaning of the prepositions *in* and *on*

The hallmark of the spatial systems in most languages is the presence of small set of terms to cover a wide range of object configurations. This apparent disparity requires that the mapping between these spatial expressions and spatial relations must abstract over many fine-grained properties of objects and their configurations. Prepositions and other spatial terms have, therefore, traditionally been thought to abstract over fine-grained properties of objects, engaging only coarse-grained *geometric* properties of object representations, such as volumes, surfaces, and axes (Landau & Jackendoff, 1993). Geometric notions like those discussed by Landau and Jackendoff (see also Talmy, 1985) have served as a cornerstone for theories of the meanings of individual spatial prepositions, and the earliest accounts of prepositions are based solely on geometry. As one example, Bennett (1975; see also Lindkvist, 1950; Miller & Johnson-Laird, 1976, Cooper, 1968; Leech, 1969) defines the preposition *in* using the highly geometric notion of an interior and a general location function, so that the expression *A is in B* for objects A and B in (1) simply means that A is located at the interior of B. By the same token, Bennett defines the preposition *on* via the location function applied to an object's surface, in (2).

(1) A is *in* B: A [locative [interior of B]]

(2) A is *on* B: A [locative [surface of B]] (both from Bennett, 1975, p. 71)

This strictly geometric definition works for canonical cases, such as the scene in Figure 1-A, of objects contained within other objects. However, relying solely on notions like interior and location as constraints on the meanings of *in* and *on* fail to account for many of the regular (i.e., non-idiomatic) uses of the terms, such as for Figure 1-B (Herskovits, 1986; Feist, 2000, Garrod et al., 1999, Coventry et al., 1994, *i.a.*) and predicts unattested uses, such as Figure 1-C.

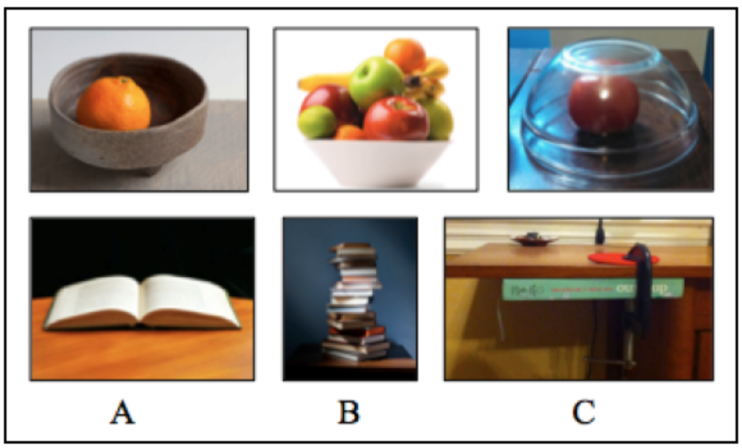


Figure 1. **Top row:** Geometry correctly predicts the acceptability of the expression "The orange is *in* the bowl" to describe case A, but not B (where the orange is on top of other fruit), and incorrectly predicts that the expression can be used for case C, where the orange is enclosed by the volume of an upside-down bowl. **Bottom row:** Geometry correctly predicts the acceptability of the expression "The book is *on* the desk" to describe case A, but not B (where the book in question is on top of other book), and incorrectly predicts that the expression can be used for case C, where the book is in contact with the under (bottom) surface of the desk.

This observation has led to a series of proposals that use geometry as a starting point for prepositional meaning, to be augmented and enriched by e.g., pragmatic processes or world knowledge. Herskovits (1986), for example, defines the semantic core of prepositions like *in*, and *on* in terms of prototypical geometric *ideal meanings*. She proposes that speakers re-imagine complex objects as volumes, points, lines, surfaces and other abstract geometric entities (cf. Marr, 1982; Landau & Jackendoff, 1993). On her view, the ideal meaning for the preposition *in*, for example, is a relation whereby a 3-dimensional volume is contained by another volume; *on* requires a surface to be contiguous with and Supported by another surface (Herskovits, 1986, p. 71). When object configurations do not readily conform to these ideal meanings, objects must be re-conceptualized and "shifted" to fit the template meaning[2]. Thus, accounts like Herskovits (1986) pragmatically enrich the under-specified geometric accounts (of Bennett and others) by positing that language users form and make use of idealized representations (or schematizations, cf. Talmy, 1985), using world knowledge to accommodate various object configurations into these templates in order to interpret prepositions like *in* and *on*. However, it is unclear what kind of world knowledge speakers use to augment ideal meanings and how speakers settle on an initial idealization in the first place – what Coventry et al. (1994) term selecting relevant geometry "in context". Enriched geometric proposals like Herskovits (1986) also leave open a number of empirical questions (making few predictions about the answers) of whether and how some relations might be better exemplars of a term.

Thus, there is a tension in using primarily geometry to define spatial prepositions. On the one hand, the coarse-grained geometry of spatial configurations provides a means by which spatial terms can encode a wide range of relations. On the other hand, however, it raises new questions about how speakers encode relations that deviate from the simple cases

[2] To see how shifts that govern the wide use of *in* might apply, consider an embedding relationship – e.g., a crack in a table – in which a negative space (the crack) must be re-imagined as an object that is then contained by a volume. For in the meaning of *on,* consider the expression "the apple on the branch": the basic relation is one of attachment, but also encompasses contiguity and Support and can, therefore, be shifted to the ideal meaning for *on*.

like those in Figure 1-A. The uses of many spatial prepositions outside of the topological cases *in* and *on* can be successfully modeled with geometry-based definitions. The terms *above, below, left of,* and *right of*, for example, can be defined using information about vertical or horizontal axes (but see Carlson-Radvansky et al., 1999). Looking at more fine-grained usage patterns and acceptability judgments, however, it turns out that speakers' use of even highly geometric prepositions is sensitive to non-geometric information. Carlson-Radvansky et al. (1999; Carlson et al., 2006) have highlighted the importance of functional properties of objects in the conditions for use of e.g., *above* and *below*. They observe, for example, that speakers' judgments of the goodness of sentences like "The coin is *above* the piggybank" depend on the position of the coin relative to functionally relevant regions of the piggybank (i.e., the slot in which coins are dropped).

Within the class of spatial prepositions, *in* and *on* appear to be unique in their degree of sensitivity to properties beyond simple geometric notions. Specifically, the type and complexity of information that speakers consider in their use of *in/on* goes beyond functional significance of individual objects (e.g., the placement of a slot in a piggybank) and instead depends on knowledge of what it means to be "contained" and "supported". This includes the relational mechanisms and physical forces that pervade Containment and Support relations, which tend to be independent of particular objects and their functions. This intuition is embodied in more recent accounts that focus on the prepositions *in* and *on* as encoding the functional relations of Containment and Support (i.e., the function of one object containing or Supporting another). Vandeloise (2005, 2010), for example, suggests that these relations should be conceptualized not as topological relations – configurations of geometric volumes or surfaces – but as functional relations composed of "container/contained" and "bearer/burden" roles. In keeping with this, the categories defined by these functional relations have a 'family resemblance'-type structure (cf. Rosch & Mervis, 1975): there are many properties of object configurations that signal e.g., a container/contained relation, and a particular configuration need not embody all of these properties to license the use of *in*. Most of the properties signaling Vandeloise's container/contained relation do not depend on a particular geometric specification or schematization of objects to be categorized as *in*. Levinson & Wilkins (2006) present a similar view on spatial descriptions more broadly, extending beyond Containment and Support expressions like *in* and *on*. They give a similar list of prototype-based conditions on object configurations that each makes the use of a "basic locative construction" – the most semantically simple expression of location (see also Levinson, Meira, et al., 2003) – in a language more or less likely. Some of these conditions are mildly functional (e.g., stereotypical vs. unusual relation between figure and ground), others are geometric (e.g., close contact vs. separation) and still others (e.g., animacy of figure and ground) are orthogonal to the function-geometry distinction (for complete set, see Levinson & Wilkins, 2004 p. 515).

Finally, Garrod and colleagues (Garrod & Sanford, 1988; Garrod, Ferrier, & Campbell, 1999; Coventry, Carmichael, & Garrod, 1994) present a series of hybrid accounts of the meanings of *in* and *on* that combine geometric and functional properties. They propose that speakers' use of *in* and *on* reflect different kinds of *locational control* – the control that one object exerts over the location of another object – between figure and ground objects. On this view, *in* and *on* are not defined through the functional relationships of Containment and Support, but rather through locational control, combined with geometric properties specific to "in-ness" and "on-ness". Successful use of *in* reflects regional enclosure with locational control, so that one object (the figure) is likely to be *in* another object (the ground) if the ground encloses the figure, and the ground (and not some other object) is controlling the location of the figure. The locational control condition differentiates cases like Figure. 2-a and 2-b (taken from Garrod et al., 1999), where the pear (shaded grey object) is judged to by *in* the bowl in case (a) but not (b), despite having the same objective degree of enclosure in both cases.

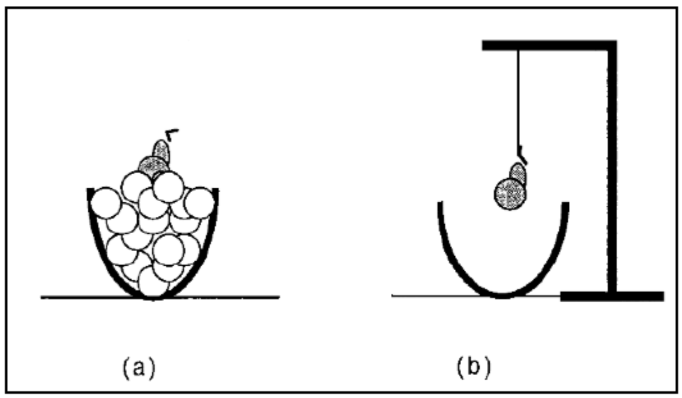


Figure 2. The pear in (a) is judged to be *in the bowl*, while the pear in (b) is not, despite the same degree of enclosure in both cases. (adapted from Garrod et al., 1999)

Similarly, successful use of *on* reflects regional contact (between surfaces) combined with locational control, relative to a unidirectional force like gravity. Speakers confidently judge a figure object to be *on* a ground object if the surfaces of both objects are in contact and the ground object (and not some other object) is controlling the location of the figure – most often by preventing it by falling.

An account of prepositional meaning that combines geometric properties like enclosure and surface contact with a functional condition of locational control seems to fit with both the clear cases of *in* and *on* use as well as the peripheral cases (cracks *in* the wall;

coats *on* a hook) that are difficult to capture with geometry alone. However, the precise interplay between the geometric and functional conditions that governs the use of *in* and *on* on these accounts is more complicated than it seems. In experiments testing speakers' confidence about *in/on* descriptions across relations that varied in the geometric properties and locational control, Garrod et al. (1999) found that for cases where regional enclosure and regional contact were high (i.e., prototypical *in* and prototypical *on* cases), judgments of locational control did not predict or influence speakers' confidence about *in* and *on*, respectively.

Geometric features have been the traditional starting point for accounts of spatial preposition (i.e., *in* and *on*) meanings. However, the range of proposals above highlights the difficulty of modeling the meanings of deceptively simple spatial expressions like *is in* and *is on* using geometry and/or function. Geometry alone fails to predict the range of regular uses for prepositions like *in* and *on* and there is no shortage of counterexamples to challenge proposed meanings for these terms. Furthermore, even when augmented by e.g., world knowledge of objects, as in the case of Herskovits (1986), the construction of these meanings is often not obvious and, while some capture intuitions about why a speaker might use an expression, the precise conditions are difficult to formally elucidate. These accounts also differ in how geometric and functional information is related to spatial term use: compare, for example, the functional relation of Vandeloise's container/contained relation, which reduces to a series of geometric and non-geometric conditions which may or may not apply, to the notion of locational control from Garrod et al. (1999), which is predicted to apply equally across cases and is only "blocked" (or reduced in importance) when geometric properties are very salient.

It is clear from the theoretical and empirical work above that the choice of particular geometric or functional properties from which to craft spatial meanings is not obvious. Choosing geometric properties inevitably results in a slew of counterexamples, and even when, for example, Containment is defined using the somewhat intuitive notion of a functional container/contained relationship, there is still a burden to make clear what the limits of that relationship are in the minds of speakers. There are, however, a number of empirical sources, not yet reviewed, that may constrain hypotheses about spatial meanings and shed light on the conceptual space that underlies spatial categories. Categorization work with pre-linguistic infants, reviewed in **Section 1.3.2** below, uses simple looking time and reaching behaviors to infer infants' knowledge and representation of spatial events like occlusion, Containment, and Support. These studies give a preliminary picture of the conceptual knowledge available prior to the outset of spatial language acquisition and, critically, are not influenced by extended experience with one language or another. Conceptual distinctions attested pre-linguistically may not be the sole source of knowledge contributing to patterns of spatial language categorization. That is, children may acquire other conceptual knowledge on the way to learning the spatial expressions of their language. With this in mind, however, pre-linguistic sensitivity to properties of spatial events marks certain conceptual information as privileged in early spatial cognition. This privileged knowledge has the potential to serve as a useful starting point for organizing the earliest central meanings of spatial expressions like *is in* and *is on*. Further studies of cross-linguistic spatial typology, reviewed and discussed in **Section 1.3.3**, compare patterns of spatial encoding across diverse languages to infer common and rare spatial categories. These patterns, in turn, are used to place constraints on the set of possible meanings that the world's spatial systems draw on to linguistically encode relations (Levinson et al., 2004).

1.3.2 Pre-linguistic spatial cognition as a basis for early spatial meanings

I turn to infancy work with the goal of identifying candidate features of Containment and Support relations that are privileged in the sense of being salient early in development (particularly, before the acquisition of language). The range of work reviewed uses measures of infant looking time – primarily in Violation of Expectation paradigms (Baillargeon, Spelke, & Wassmerman, 1985), where infants are predicted to look longest to scenes or events that are at odds with their knowledge of the world – in combination with action-based reaching measures (Hespos & Baillargeon, 2008) – in which infants are predicted to reach more frequently for objects that they reason to be accessible – to infer knowledge of and sensitivity to particular spatial properties. This sensitivity, in turn, serves as a starting point for thinking about Containment and Support as spatial categories and the conditions under which Containment and Support expressions like *is in/on* are likely to be used. Later I will use these pre-linguistically attested properties to delineate a set of core features for Containment and Support relations, around which spatial meanings can be organized.

The development of spatial relational knowledge is thought to be a protracted process that starts with object identification – sensitivity to familiar vs. novel objects – followed by differentiating spatial relations (e.g., an object contained vs. Supported by another object) for familiar objects, followed, at last, by sensitivity to different spatial relations independent of the identity of objects (Casasola & Cohen, 2002). This proceeds on different time scales for different categories of spatial relations. Infants are able to form object-independent representations of Containment relations by 6 months of age (Casasola, Cohen, & Chiarello, 2003) but take 10-14 months to form similar representations for Support relations (Casasola, 2005), suggesting a separation between these broad spatial categories.

In a similar vein, many infant researchers, most notably in the tradition of Baillargeon, Spelke and colleagues (Baillargeon, 1995; Baillargeon et al., 1992; Hespos & Baillargeon, 2001, 2006, 2008; Hespos & Spelke, 2007; *inter alia*), propose that early spatial knowledge is a two-part system that begins with infants' identification of initial spatial concepts: conceptual categories of spatial events, such as Containment, Support, and occlusion. Within each initial concept, infants must subsequently learn to attend to specific event variables like height, width, and contact, over time refining their representation of the initial concept for e.g., guiding action and spatial reasoning. Infants must (re)learn the importance of a particular variable for each event, so that, for example, an infant will successfully attend to an object's height in occlusion events, reasoning that a tall object cannot be fully occluded by a short wall, but will fail to attend to the same height variable for Containment events – to reason that a tall object cannot be fully contained by a short object – until several months later (Hespos & Baillargeon, 2001, 2006). These findings and others (see e.g., Hespos & Baillargeon, 2008; Baillargeon et al., 1992) are consistent with the work of Casasola and colleagues and underscore the preliminary notion that Containment and Support are separate salient concepts formed early in the development of spatial cognition.

Early event variables for Containment and Support, reviewed below, are privileged types of information that infants are equipped with before they acquire language. As such, properties based on these variables are good candidates for the earliest meanings of Containment and Support expressions like *is in* and *is on*. In the proposed work, I further suggest that these properties are manifest not only in early-acquired meanings for these expressions, but also play a primary role in accounting for the extended range of cases covered by *in* and *on*.

In order to successfully reason about Containment events, Hespos and colleagues observe that infants must attend to several properties of the objects in an event as well as properties of the relations between objects in the event. Looking time measures reveal that, by 3.5 months of age, infants make assumptions about the solidity of containers and are, therefore, surprised (evidenced by longer looking times) when a contained object transgresses the boundaries of its container but are not surprised when occluded object moves beyond the limits of its occluder (Hespos & Baillargeon, 2001). The same looking time study demonstrated that 3.5-month-olds also successfully reason that in order for an object to become contained by another (i.e., move into a Containment relation), the container must have an open top. Taken together, infants' sensitivity to these two variables (solidity and open vs. closed-top containers) suggests that they are equipped early on with some notion of *enclosure* of one object by another (solid) object within Containment relations.

In a different study, Hespos and Spelke (2007) assessed infants' sensitivity to the degree of fit (i.e., amount of empty space) between objects in a Containment relation and expectations about whether objects should move together or separately, depending on the amount of empty space between them. Their results revealed that, by 5 months, infants have strong expectations about constraints placed on the (horizontal) movement of one object contained by another: when there is a lot of empty space between an object and its container, infants expect the objects to move separately and are surprised when the objects display coordinated movement. Conversely, when there is little empty space between objects, infants are surprised when object display independent (i.e., non-coordinated) patterns of horizontal movement. From this and other studies (see e.g., Hespos & Spelke, 2004), we can infer yet another privileged property of Containment relations, which I will refer to as *volume match*: the presence or absence of empty space between two objects in a Containment relation.

Infants' reasoning about Support relations differs from Containment relations, both in the nature of the variables and the age at which sensitive to these variables arises. Baillargeon and her colleagues (Baillargeon 1995; Baillargeon et al, 1992; Hespos & Baillargeon, 2008) used a combination of looking time (violation of expectation) and reaching measures to identify two primary variables, based on contact between objects, that infants attend to in their reasoning about Support. The first variable concerns the type of contact required for an object to Support another: 5.5-month-old infants are surprised and look longer to events in which an object remains Supported after being placed against the side surface of another object but are not surprised when an object remains Supported after being placed on the top surface of an object (Baillargeon et al., 1992; Hespos & Baillargeon, 2008). Along these lines, infants given the opportunity to reach for an object in either relation reach for the object Supported from below reliably more often, reasoning that the object Supported from the side is permanently affixed to the Supporting object (Hespos & Baillargeon, 2008). These findings provide evidence for the privileged nature of vertical object configurations, a property I will call *vertical position*, in early reasoning about Support relations.

The second event variable identified in this set of studies is the proportion of contact between an object and a Supporting surface. Hespos and Baillargeon (2008) observed that infants were surprised and looked longer at events in which an object was placed on another so that only 15% of its surface was in contact with the Supporting object, compared to events in which 100% of the surface was in contact. Similarly, infants reached for objects with 100% contact reliably more than 15% contact, again reasoning that objects in the latter condition were more or less permanently attached (Hespos & Baillargeon, 2008). This early sensitivity underscores another privileged property of Support relations, which I will term *surface match*.

Studies of infant spatial cognition furnish us with a set of candidate properties with which to model the meaning and use of spatial expressions. In the proposed dissertation, I use the infant work reviewed above to identify four such properties – two for the encoding of Containment relations, two for Support relations – that I suggest are manifest not only in the central uses of expressions like *is in* and *is on* (the apple is in the bowl; the book is on the table), but also in non-central uses (e.g., the light bulb is in the socket; the coat is on the hook). I refer to these properties, listed below in (5) as *geometric* properties of relations, in contrast to the functional property of locational control, which will also be considered in the proposed work.

(5) Geometric properties of Containment and Support relations:

Containment	a. Enclosure: one object surrounding another
	b. Volume match: the amount of empty space between two objects
Support	c. Vertical position: the vertical position of one object relative to the other
	d. Surface match: the proportion of one object's surface in contact with the surface of the other

Infants are thought to come pre-equipped to learn the spatial categories for any language, on par with phonemic category sensitivity (Hespos & Spelke, 2004, 2007), suggesting that these properties should not be specific to the spatial meanings of English alone. Along these lines, Gentner and Bowerman (2009) outline a sophisticated proposal for linking early spatial meanings to variation in spatial systems across languages. Their Typological Prevalence hypothesis predicts that categorization patterns that are easier to learn should be more frequently attested in spatial language systems of the world and should arise earlier and with fewer errors over the course of acquisition. I return to this hypothesis in the next section, where I briefly review work on spatial encoding across languages in the tradition of descriptive typology.

1.3.3 Cross-linguistic consistency and variation as a basis for spatial meanings

Data from diverse language groups is complimentary to the pre-linguistic work reviewed above. Instead of developing a feature inventory on the basis of spatial knowledge present before the onset of language acquisition, cross-linguistic data can be used to infer relevant conceptual feature dimensions that speakers of all languages may attend to from distinctions that are lexicalized by speakers of some languages. In particular, a language may choose to lexically mark some spatial distinctions but not others, and the tendency for spatial information to be encoded in surface forms of a language gives rise to a typology of encoding across many languages (Talmy, 1985).

On this typological view, if a particular feature dimension is considered a possible contributor to the meaning and use of a spatial expression, we should expect the spatial language system of *some* language to reflect variation on the feature. However, lexical distinctions are not the only means by which a language can reflect conceptual distinctions. The current work uses a more sensitive measure of language use, namely the difference in the rate at which speakers use a single expression to encode conceptual distinctions ("soft" cuts in semantic space). With this caveat in mind, I discuss a handful of case studies in different languages where lexical distinctions are made on the basis of the geometric feature dimensions I propose in the dissertation.

Enclosure in English and Jaminjung. The complete enclosure of one object (the figure) by another (the ground) is an aspect of Containment configurations that tends to be marked in English, by the term *inside* discussed later in the proposed research, as well as in other non-European languages. The Australian language Jaminjung (Schultze-Berndt, 2006) has a set of coverbs dedicated to expressing notions of convex enclosure of a figure object by a ground. Speakers of Jaminjung make use of the related coverbs *walthub* and *walyag* (roughly glossed as *enclose*) to encode the relationships in scenes like Figure 3. Use of these spatial terms in Jaminjung does not seem to depend on the amount of empty space between figure and ground objects (i.e., the volume match, discussed next), suggesting that these Containment features could be somewhat orthogonal for spatial encoding.

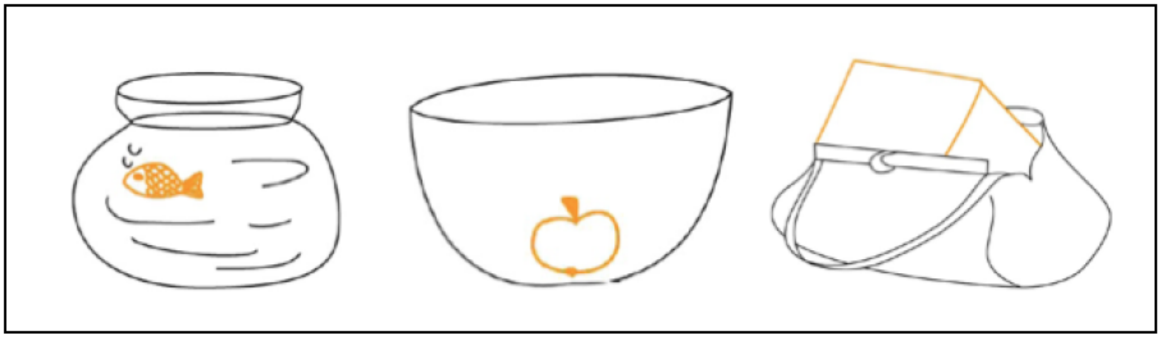


Figure 3. Relationships between figure objects (in orange ink) and ground objects (in black) that are encoded by enclosure-sensitive coverbs in Jaminjung. Adapted from the Topological Relations Picture Series (TRPS), Bowerman & Pedersen (1992).

Volume match (or "fit") in Korean. Evidence for the linguistic encoding of the "fit" of a spatial configuration comes from speakers of Korean, who use different verbs to systematically expresses "tight-fit" and "loose-fit" dimensions of spatial events. Bowerman and Choi (2001) observe that Korean speakers use at least three different verbs to encode events based on the nature of their fit. The verb *kkita* is for interlocking ("tight-fit") cases such as putting a cap on a pen or a book in a fitted box cover (Figure 4-a) and contrasts with *nheta*, which is used for "loose-fit" Containment such as putting an apple in a bowl or a book in a bag (Figure 4-b), and *nhota*, which is used to encode cases where an object is put on a horizontal surface (such as a cup on a table; Figure 4-c).

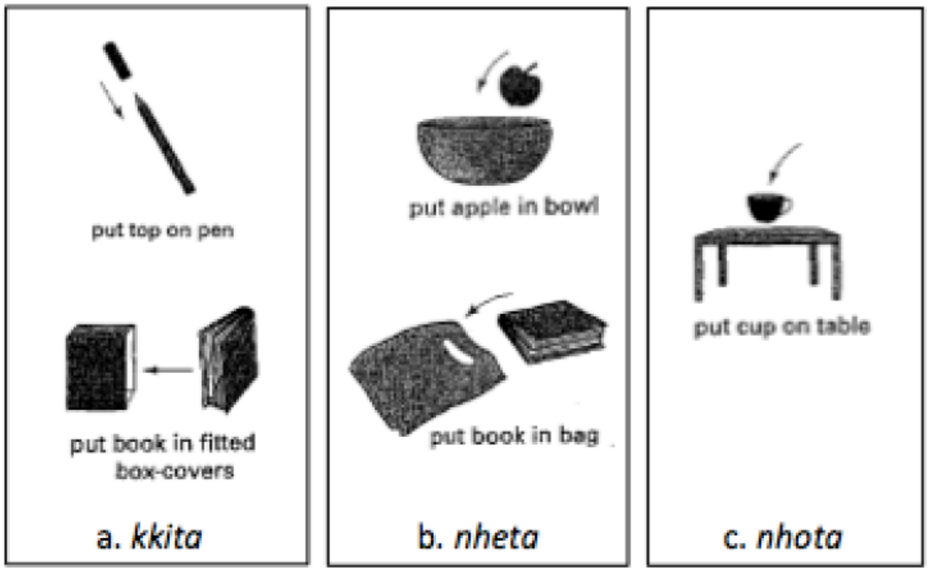


Figure 4. Spatial events encoded by the Korean verbs of "fit" *kkita* (a.), *nheta* (b.), and *nhota* (c.). Adapted from Bowerman and Choi (2001).

Vertical position in Dutch. Dutch speakers, one well-studied example, are sensitive to the position of a Supporting ground object in relation to the figure object being supported. Specifically, Gentner and Bowerman (2007; see also Vandeloise, 2003) note that the Dutch inventory of spatial expressions includes three terms that mark the distinction between relations in which an object is Supported by another object from below and relations in which Support is achieved through other means. The term *op* tends to be reserved for cases like an apple on a table (Figure 5a), sometimes extending to cases of permanent contact, such as paint on a wall (Figure 5b). By contrast, Dutch speakers use other spatial terms for cases that do not involve Support from below: *aan* is used to encode hanging and attachment relations like clothes on a clothesline (Figure 5c), while *om* is used for cases of encirclement such as the wrapper on a piece of gum (Figure 5d).

Figure 5. Spatial relations encoded by the Dutch expressions *op* (a. and b.), *aan* (c.), and *om* (d.).

Surface match (or "contact") in Yêlí Dnye. Speakers of *Yêlí Dnye*, an isolate language spoken in Papua New Guinea (Levinson, 2006), make use of a small inventory of spatial postpositions to encode object configurations. In particular, the term *yedê* (roughly glossed as *on a surface*) is used to express surface contact independent of the (vertical) position of the figure and ground objects. That is, speakers use *yedê* to encode relations in which the ground object is horizontal (a cat on a mat; Figure 6a.), vertical (raindrops on a window; Figure 6b.), and even embedded (a design on a t-shirt; Figure 6c.), provided that the surfaces of the figure and ground objects are in sufficient contact with one another.

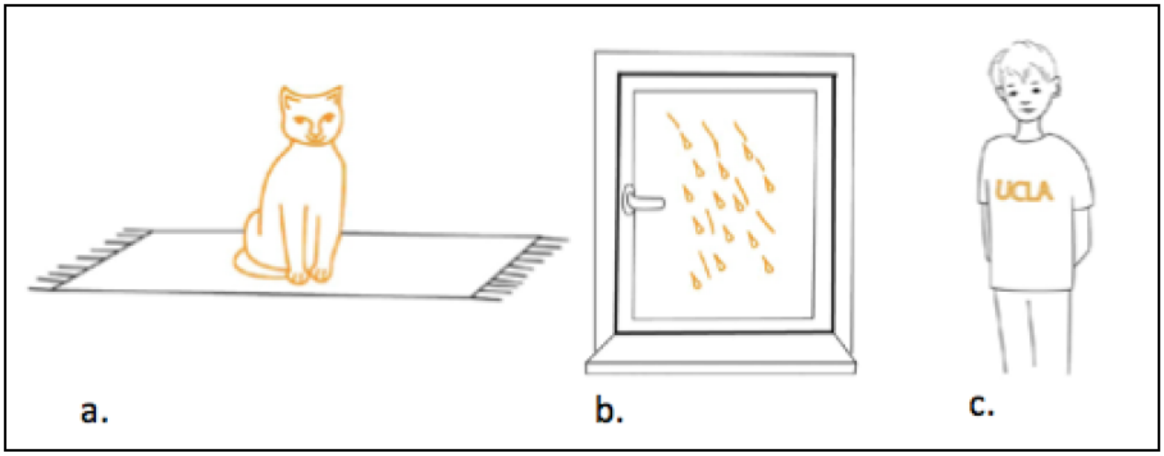


Figure 6. Relationships between figure objects (in orange ink) and ground objects (in black) that are encoded by contact-sensitive postpositions in Yêlí Dnye. Adapted from the TRPS, Bowerman & Pedersen (1992).

The division of terms in languages like Jaminjung, Korean, Dutch, and Yêlí Dnye is reminiscent of the sensitivity that pre-linguistic infants show to different features of Containment and Support relations, discussed in Section 2.3.2 above. Although these cases can all be encoded with the English expressions *is in* and/or *is on*, work from Johannes et al. (2012, in prep) and Landau et al. (submitted) demonstrates that English speakers are sensitive to these distinctions in the rate at which they use *is in* and *is on* to encode various Containment and Support relations.

1.4 Overview of thesis

My goal in this thesis is to systematically relate the mature and developing use of different types of spatial expressions to speakers' conceptualization of a small set of geometric and functional features of Containment and Support relations. Where child (developing) spatial expression use differs from adult (mature) expression use, I examine the extent to which the following three factors play a role: children's knowledge of geometric and functional features, the mappings between child feature knowledge and child language use, and the influence of parental input on this relationship.

The studies that contribute to this research program are reported as follows: In Study 1, I ask whether variation in a few geometric features of Containment and Support, and a single functional feature – locational control, which applies to both categories – can account for the distribution of multiple types of spatial expressions in the spatial descriptions of mature speakers. In Study 2, I ask the same question of developing spatial language use, focusing on the developing relationship between geometric and functional features and different types of spatial expressions. I examine how children's geometric and functional feature knowledge and use of particular spatial expressions differs from adults' and whether these differences result in fundamentally different mappings from features to language for children. Finally, in Study 3, I model the influence of parental input on children's developing feature-language mapping. I ask whether parents' child-directed spatial language use mediates the relationship between children's spatial expression use and estimates of both children's feature knowledge, as well as estimates of adults' feature knowledge.

Chapter 2

Study 1: Can variation in geometric and functional features of spatial relations account for variation in mature speakers' spatial expression choice?

In Study 1, I validate a hypothesized relational feature space for Containment and Support relations through a simple image-rating task (Experiment 1). I ask English-speaking adults to rate a sample of spatial items on a series of geometric and functional features. I then use these values to ask whether variation in geometric and functional features of relations can predict the use of different types of spatial expressions produced by a separate group of adult speakers (Experiment 2). Finally, I gather image ratings for a set of non-relational features (i.e., features that apply to one object or another, but not to the relation between the objects) in order to show that, while these non-relational features are plausible candidates for determining spatial encoding, they fail to account for speakers' sensitivity in expression choice (Experiment 3).

Experiment 1: Establishing a geometric and functional feature space

The aim of Experiment 1 was to empirically validate a set of hypothesized geometric and functional features across a range of diverse Containment and Support relations. Containment and Support items were chosen so as to vary along two geometric dimensions: Enclosure and Volume (match) for Containment relations, and Vertical (position) and Surface (match), see Table 1 for the complete list. This initial ordering of stimuli was by hypothesis only, however, and naïve adults were recruited to verify these orderings. Additionally, I was interested in two functional features: Location Control (of the figure object by the ground) for Containment, and Support against gravity (of the figure object by the ground object) for

Support relations, but had no prior predictions about how items would be ordered according to these functional features, which seem to depend on knowledge of particular objects, forces, and mechanisms.

For each of the Containment and Support relation sets, I selected 64 spatial relation items and, based on my own intuitions, divided them into quartiles along the two geometric feature dimensions for each relational domain. This process yielded a hypothesized four-by-four space of crossed feature quartiles, with four items in each feature quartile combination – for example, the Containment space has four items predicted to be in the first quartile for Enclosure and the first quartile for Volume. The hypothesized geometric feature spaces across items are shown in Figure 7, for Containment relations, and Figure 8, for Support relations.

Figure 7. Sample of 64 Containment items ordered, by hypothesis, along the geometric feature dimensions of Enclosure and Volume Match. Items were not ordered by hypothesized functional feature (Location Control) values.

Figure 8. Sample of 64 Support items ordered, by hypothesis, along the geometric feature dimensions of Vertical Position and Surface Match. Items were not ordered by hypothesized functional feature (Support against gravity/Location Control) values.

Method.

Participants were 50 adults recruited from the JHU internal experimental subject pool and participated through a self-paced online interface for course credit. Each participant was randomly assigned to provide ratings for either Containment items (N=25; 14 males) or Support items (N=25; 12 males).

Participants were shown a set of 64 items of objects in either Containment relations (items in Figure 7) or Support relations (items in Figure 8), presented one at a time in random order. For each item, participants were instructed to consider the two salient labeled objects in the item and provide ratings on a 4-point scale for each of three separate features. Features, rating prompts, and the response scale endpoints provided to subjects are given below in Table 1. Participants were familiarized with the task through practice image accompanied by a comprehensive explanation of each feature.

Table 1. Rating prompts and scales provided to subjects in the feature rating task for Containment (top) and Support (bottom) items.

Containment Feature	**Rating prompt**	**Scale endpoints [4…1]**
Enclosure	*How much of object A is enclosed by object B?*	All of A is enclosed by B Hardly any of A is enclosed by B
Volume Match	*How much empty space is present between object A and object B?*	There is a lot of empty space between A and B There is hardly any empty space between A and B
Control	*If object B is moved, how likely is it that object A will move with it?*	A is extremely likely to move where B moves A is unlikely to move where B moves
Support Feature	**Rating prompt**	**Scale endpoints [4…1]**
Vertical Position	*How much of object A is situated higher than object B?*	All of A is higher than B None of A is higher than B
Surface Match	*How much of object A's surface is in contact with object B?*	All of A is in contact with B Hardly any of A is in contact with B
Gravitational support	*If object B is moved, how likely is it that object A will fall?*	A is extremely likely to fall if B moves A is unlikely to fall if B moves
Control	*If object B is moved, how likely is it that object A will move with it?*	A is extremely likely to move where B moves A is unlikely to move where B moves

Results.

Each of the 25 participants provided ratings on each of the three features for all 64 items (192 ratings per participant) for either Containment or Support relation sets. Ratings were then aggregated across participants. All reported analyses use these aggregate attested ratings, with one mean rating per feature per item. Results are reported separately for Containment and Support relations.

Containment features

Analysis 1. Are participants' attested geometric ratings consistent with the hypothesized geometric ordering of items?

The attested Enclosure and Volume ratings were consistent with the hypothesized ordering of Containment items along each feature dimension. Figure 9 shows the relationship between predicted orderings and attested ratings for the two geometric feature dimensions (Enclosure and Volume; for ease of interpretation, the attested organization is also shown without preserving distances between item ratings in Figure 10). Additionally, I calculated a deviation score for each participant's rating (from 1 to 4) and the predicted quartile (from 1 to 4). Mean deviation scores, the distance between predicted quartiles and attested ratings, were 0.59 for Enclosure ratings and 0.52 for Volume ratings. These scores suggest that items fell, generally, within their predicted quartiles for Enclosure and Volume, as a deviance score of 1 (or greater) would suggest deviance of one quartile (or more).

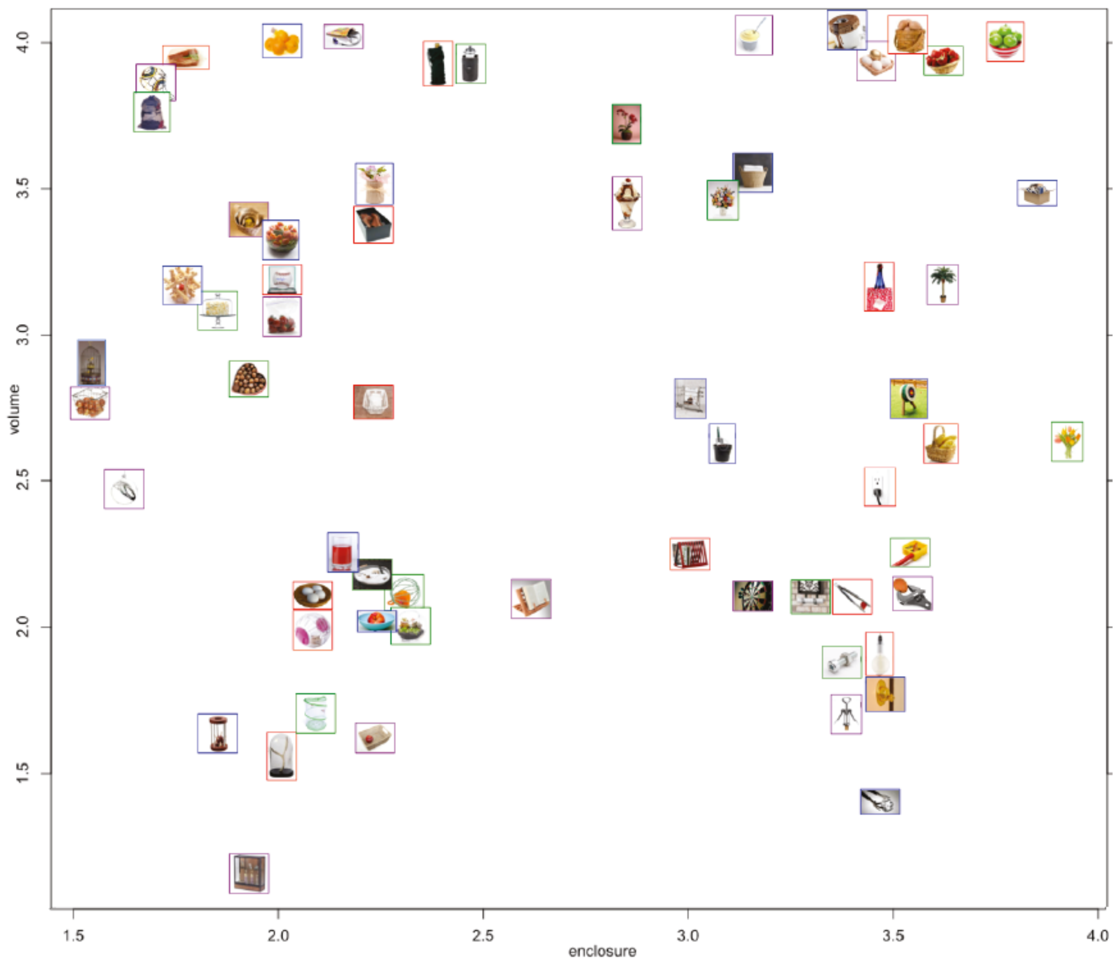


Figure 9. Containment items plotted according to attested ratings of Enclosure (x-axis) and Volume (y-axis).

Figure 10. Attested groupings of Containment items across quartiles of Enclosure and Volume Match.

Analysis 2. Are the attested values of one feature systematically related to the attested values of another feature?

The distribution of all 64 Containment items along the three feature dimensions is shown in Figure 11. The correlations between Enclosure and Volume ratings were low ($r=0.007$), consistent with their treatment as separate feature dimensions. However, much of the variation in Control ratings can be accounted for by variation in Enclosure ratings ($r = 0.497$), but less so by variation in Volume ratings ($r = 0.312$). This suggests that subjects are, to some extent, considering the degree of Enclosure (of one object by another) as a factor in their estimates of Control: whether one object controls the movement of another.

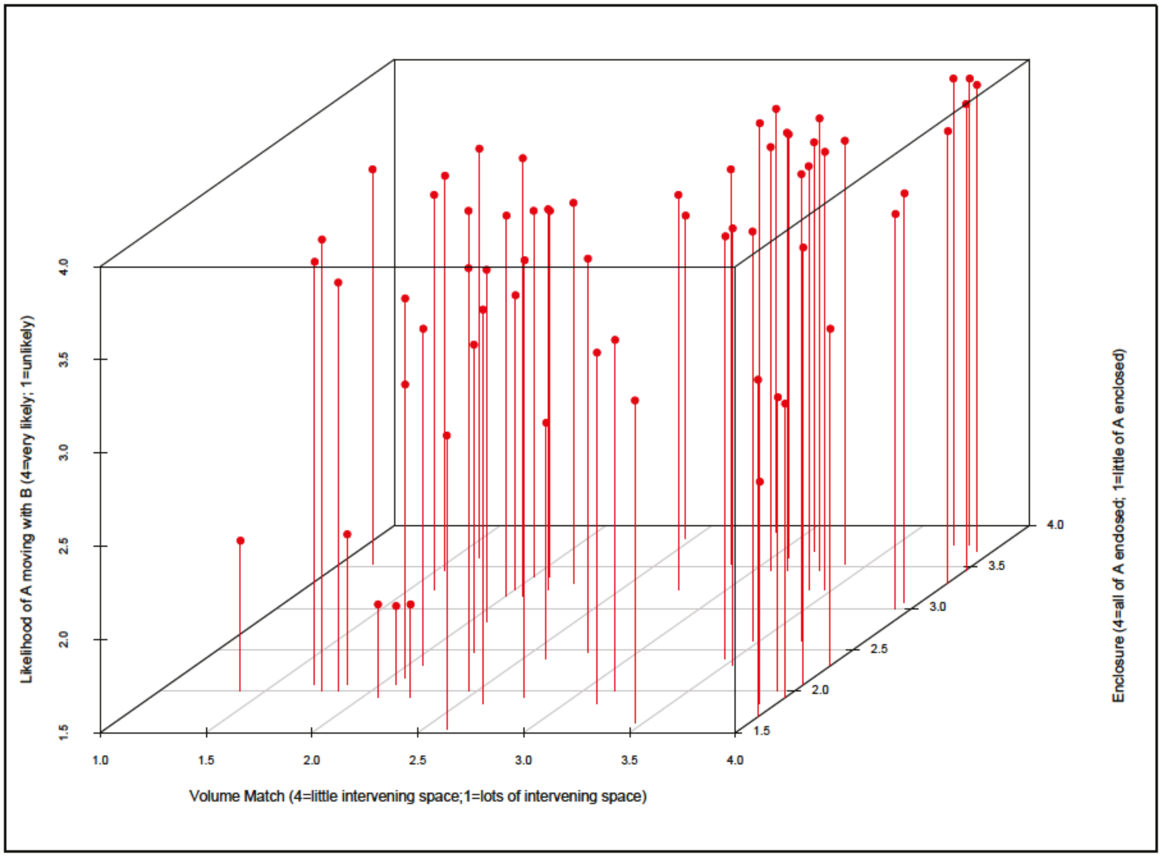


Figure 11. Distribution of Containment items along three feature dimensions: Volume match (x-axis), Enclosure (y-axis), and Control (z-axis).

Support features

Analysis 1. Do participants' attested geometric ratings accord with the hypothesized geometric ordering of items?

Similar to the geometric features in Containment, the attested Vertical and Surface ratings were also consistent with the hypothesized ordering of Support items along each feature dimension. Figure 12 shows the relationship between predicted orderings and attested ratings for the two geometric feature dimensions (Vertical and Surface; the attested organization is also shown, without preserving distances between item ratings, in Figure 13). The calculated mean deviation scores, the distance between predicted quartiles and attested ratings, were 0.47 for Vertical ratings and 0.79 for Surface ratings – higher than the deviation for Containment feature ratings, but still within one quartile.

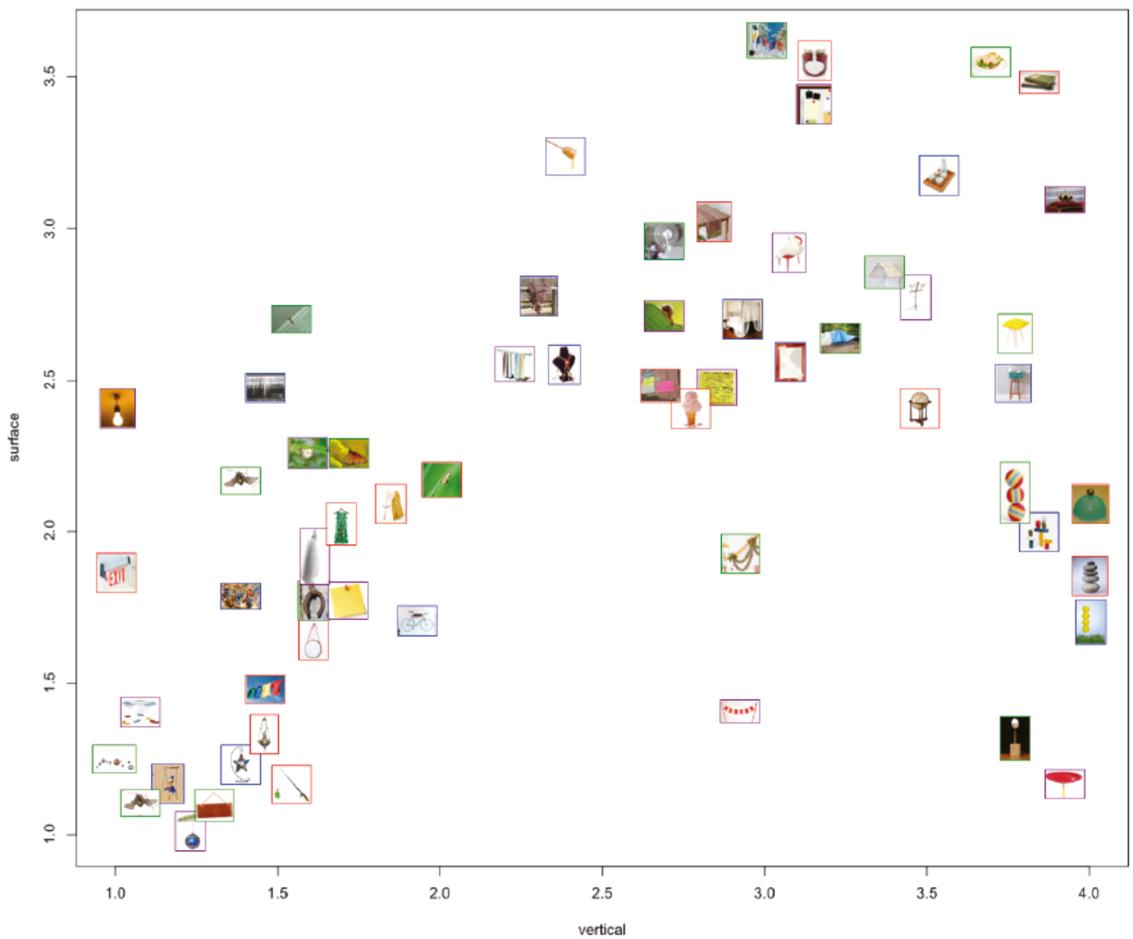


Figure 12. Support items plotted according to attested ratings of Vertical Position (x-axis) and Surface Match (y-axis).

Figure 13. Attested groupings of Support items across quartiles of Vertical position and Surface Match.

Analysis 2. Relationships among attested ratings for geometric features and Control.

Figure 14 shows the distribution of all 64 Support items along the three feature dimensions. Vertical and Surface ratings were moderately correlated across items (r = 0.485), which may be a result of the selection of items – relations in which the figure object was below the ground object tended, also, to have very little surface contact. Vertical ratings were also moderately correlated with Control ratings (r =0.548), suggesting that the relative vertical positions of objects factored into subjects' judgments about the control of one object by the other. Surface ratings, however, were not reliably correlated with Control ratings.

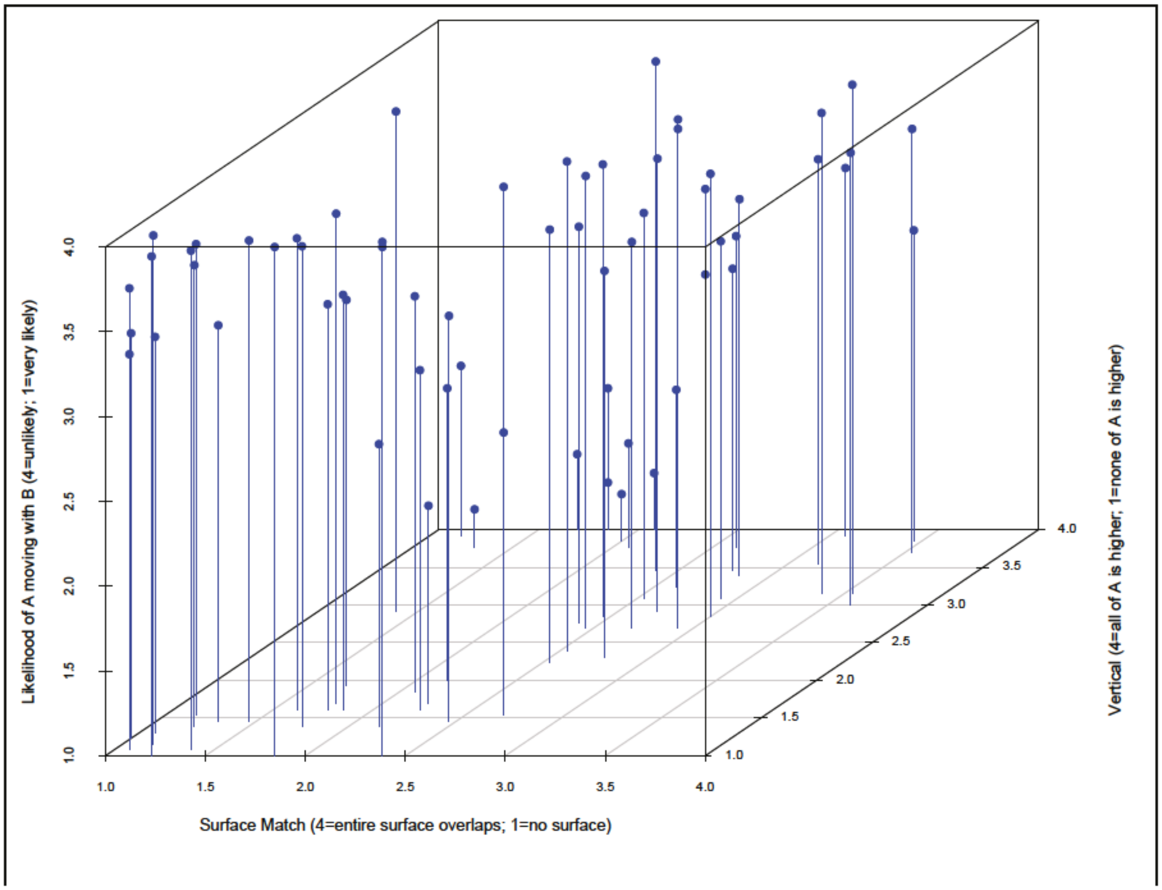


Figure 14. Distribution of Support items along three feature dimensions: Surface match (x-axis), Vertical position (y-axis), and Control (z-axis).

Discussion.

The results of Experiment 1 demonstrate, first and foremost, that the hypothesized geometric and functional features are salient properties of object configurations that naïve participants can consistently judge from images. Participants' judgments of these features varied systematically over samples of Containment and Support items. For geometric features, where items were predicted to order in a certain way, participants' ratings were well aligned with the predicted ordering of items along each feature dimension.

The features also showed co-variation across items: of interest were correlations between ratings of geometric features and the functional feature Control. Control ratings were moderately correlated with Enclosure ratings for Containment items – fully-enclosed items (leftmost column of Figure 1.) tended to receive the highest Control ratings – and with Vertical ratings for Support items, where items with figure objects positioned completely above ground objects (leftmost column of Figure 2.) tended to receive the highest Control ratings. One way of interpreting these relationships between geometric features and Control is to consider Enclosure and Vertical position as privileged (geometry-based) mechanisms by which a ground object can exert locational control over a figure object. The fact that these geometric features are only moderately correlated with Control suggests that there are also other mechanisms by which objects control other objects within Containment and Support relations.

Additionally, for Support (but not for Containment), ratings of geometric features, Vertical Position and Surface Match, were also moderately correlated. This is likely due to the sample of items for Support, rather than the co-occurrence of the features in support relations, more generally: many items in which the figure object was below the ground object (low ratings for Vertical Position) also had very little contact between objects' surfaces (low ratings for Surface Match; e.g., a fish on a fishing pole, a bat hanging upside down from a branch).

Experiment 2: Relating geometric and functional features to spatial expression use

Experiment 1 established and empirically validated a feature space, made up of both geometric and functional features, over a large sample of Containment and Support items.

The aim of Experiment 2 was to systematically relate the variation in geometric and functional features across spatial items to variation in speakers' choices of spatial expressions for those same items in a language production task.

To do this, I asked a new set of participants to view each item and provide a spatial description, as an answer to the questions "Where is the [figure object]?" I then identified several types of spatial expressions, with the goal of relating the values of particular features or combinations of features to the probability that a participant would use a particular expression across all of the items. The results of this experiment shed light on the systematic conditions under which speakers choose to use e.g., a prepositional spatial expression like *is in* or *is on*, versus a lexical verb expression (e.g., *connect to*, *hang from*) or other preposition-based expression (e.g., *is over*, *is below*).

Method.

Participants were a new set of 50 adults (24 males) recruited from the JHU internal experimental subject pool and participated through an online interface for course credit. Each participant was randomly assigned to provide descriptions for either the 64 Containment items (N=25; 13 males) or the 64 Support items (N=25; 11 males) used in Experiment 1. Items were presented in random order and, for each image, participants were asked to provide a description of the spatial relation between the two salient labeled objects, A and B, by answering the "Where is Object A (in relation to Object B)?"

Results.

All 25 participants provided a single description for each of the 64 Containment or Support items. Participants always gave their descriptions in the following form: "Object A [spatial expression] object B", where the spatial expression included one or more verbs, a preposition, and optional modifiers. Descriptions were coded for the presence of one of multiple types of spatial expressions, discussed separately for Containment and Support relations, below.

Mixed effects multinomial logistic regression analyses were used to determine how well each feature, or principled combinations of features, predicted the use of spatial expression type over all 64 Containment or Support items. One model was computed for Containment items and a separate model was computed for Support items. Both models featured Subject and Item random effects on the model intercepts. For ease of presentation, I present and discuss model results separately for each expression type, even though log-odds coefficients are estimated jointly across all expression types. As a measure of model accuracy, I report correlations between the model-fitted probability of using a particular spatial expression (for each item) and the observed rate with which participants used the expression. Unless stated otherwise, all correlations are significant at $p<.01$.

Containment descriptions

For the purpose of the multinomial analysis, participants' Containment descriptions were coded as matching one or more of the following four spatial expressions.

(1) BE + inside (e.g., A *is inside* B)

(2) BE + in or inside (e.g., A *is in(side)* B)[3]

(3) Lexical Verb + Preposition[4] (e.g., A *is held by* B)

(4) BE + Other Preposition (e.g., A *is near* B)

[3] The spatial expression *is inside* was coded as belonging to both *is inside* and *is in(side)* for Containment and these instances were used in both sets of regression models. This was also true of *is on top* for Support.
[4] Coding of lexical verb + preposition expressions included the prepositions *in* and *inside*. Lexical verb + in(side) expressions were not frequent enough to code as a separate expression type.

Figure 15 shows the distribution of these expression types across a subset of the 64 Containment items. Table 2 gives a summary of the model coefficients and correlations between model-fitted values and observed rates of use for each expression type.

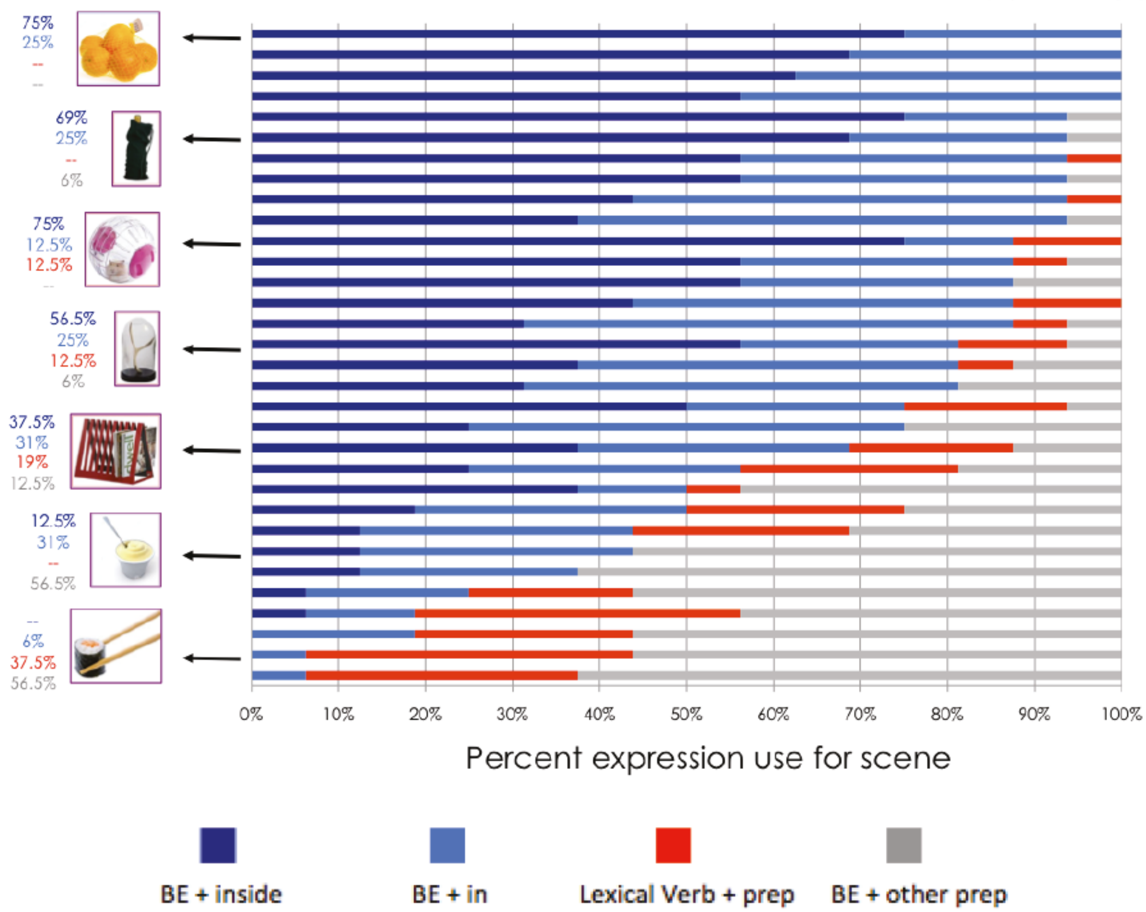


Figure 15. Distribution of main expression types for Containment descriptions across a subset of the 64 items. Individual items are on y-axis; percent use for different expressions is on x-axis.

Table 2. Multinomial model summary with correlations between model-fitted values and observed expression use. All values are significant (p <.05) except where noted otherwise (*ns*).

	BE + inside	*BE + in(side)*	*Lexical verb + preposition*	*BE + other preposition*
Intercept	**-1.68**	**-1.78**	**3.48**	**3.26**
Enclosure β	**0.84**	**0.47**	**-1.05**	**-1.20**
Volume match β	-0.05 *(ns)*	0.02 *(ns)*	**-0.49**	**-1.13**
Control β	**0.68**	**0.48**	**-0.70**	-0.01 *(ns)*
Model fit-observed correlation (r)	0.68	0.67	0.63	0.63

Adults' use of [BE + inside] and [BE + in(side)] is positively predicted by Enclosure and Control ratings

Enclosure and Control ratings, together, positively predicted the use of both *is inside* (r = 0.68) and *is in(side)* (r=0.67). Items rated highest on the combination of Enclosure and Control, like the sample item in Figure 16-A, were most likely to be described with *is in(side)* and items rated lowest (Figure 16-B) were least likely to be described with *is in(side)*. This relationship was especially strong for the expression *is inside*.

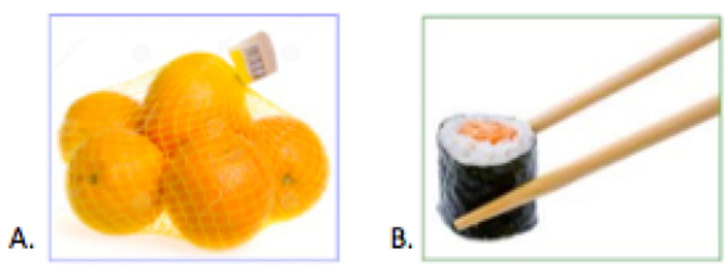


Figure 16. Items rated high (A) and low (B) on the combination of Enclosure and Control were respectively more or less likely to be described with the expression *is in(side)*.

Adults' use of [lexical verb + preposition] is negatively predicted by Enclosure and Volume ratings

Enclosure, Volume, and Control, together, negatively predicted the use of *lexical verb (+ preposition)* expressions (r = 0.63). Items rated lowest on Enclosure and lowest on Volume (i.e., items with lots of empty space between objects), as in Figure 17-A, were most likely to be encoded by a lexical verb expression like *held by* or *screwed into*. The probability of using a lexical verb expression further increased if the item was also rated low on Control. This relationship suggests that lexical verb expressions are most likely to be recruited in the absence of this particular type of geometry-based relational information.

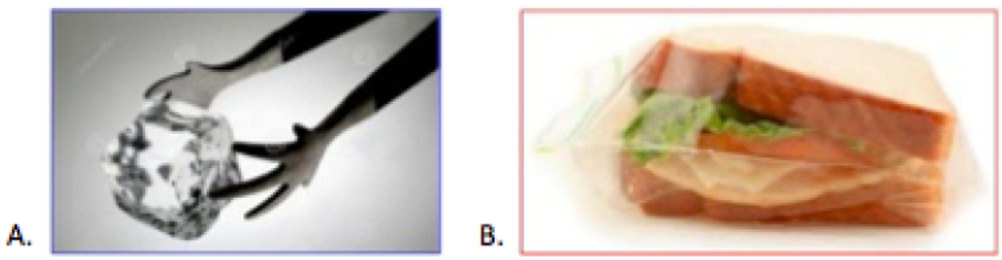


Figure 17. Items rated low (A) and high (B) on the combination of Enclosure, Volume, and Control were respectively more or less likely to be described with *lexical verb* expressions (e.g., *screwed into*).

Adults' use of [BE + preposition] is negatively predicted by Enclosure and Volume ratings

Enclosure and Control, together, negatively predicted the use of the copula *be* with a preposition other than *in(side)* – e.g., *is near/beside/in the middle of* – (r=0.63). Items rated lowest on the combination of Enclosure and Volume, as in Figure 18-A, were most likely to be encoded by a copular verb + *other preposition*. This suggests that speakers use these expressions to encode other spatial properties of the item (such as proximity or regional location) when there are no strong geometric or functional cues to Containment.

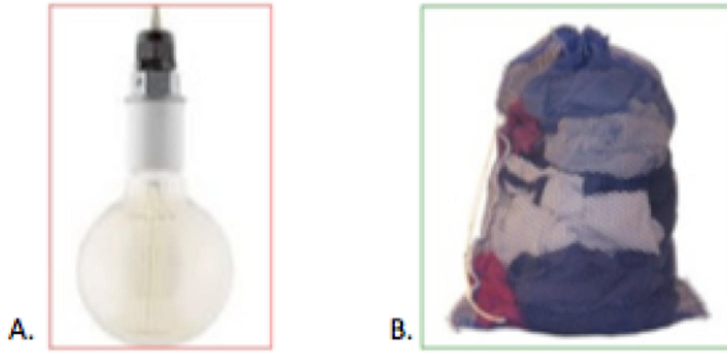


Figure 18. Items rated low (A) and high (B) on the combination of Enclosure and Control were respectively more or less likely to be described with *copular verb + other preposition* expressions (e.g., *is near/below/under/in the middle of*).

Support descriptions

Participants' Support descriptions were coded as matching one or more of the following four spatial expressions.

(1) BE + on top (e.g., A *is on top of* B)

(2) BE + on or on top (e.g., A *is on (top of)* B)

(3) Lexical Verb + Preposition[5] (e.g., A *is hanging from* B)

(4) BE + Other Preposition (e.g., A *is under* B)

Figure 19 shows the distribution of these expressions across a subset of the 64 Support items. Table 3 gives a summary of the model coefficients and correlations between model-fitted values and observed rates of use for each expression type.

[5] As in Containment, the coding of lexical verb + preposition expressions for Support included the prepositions *on* and *on top*.

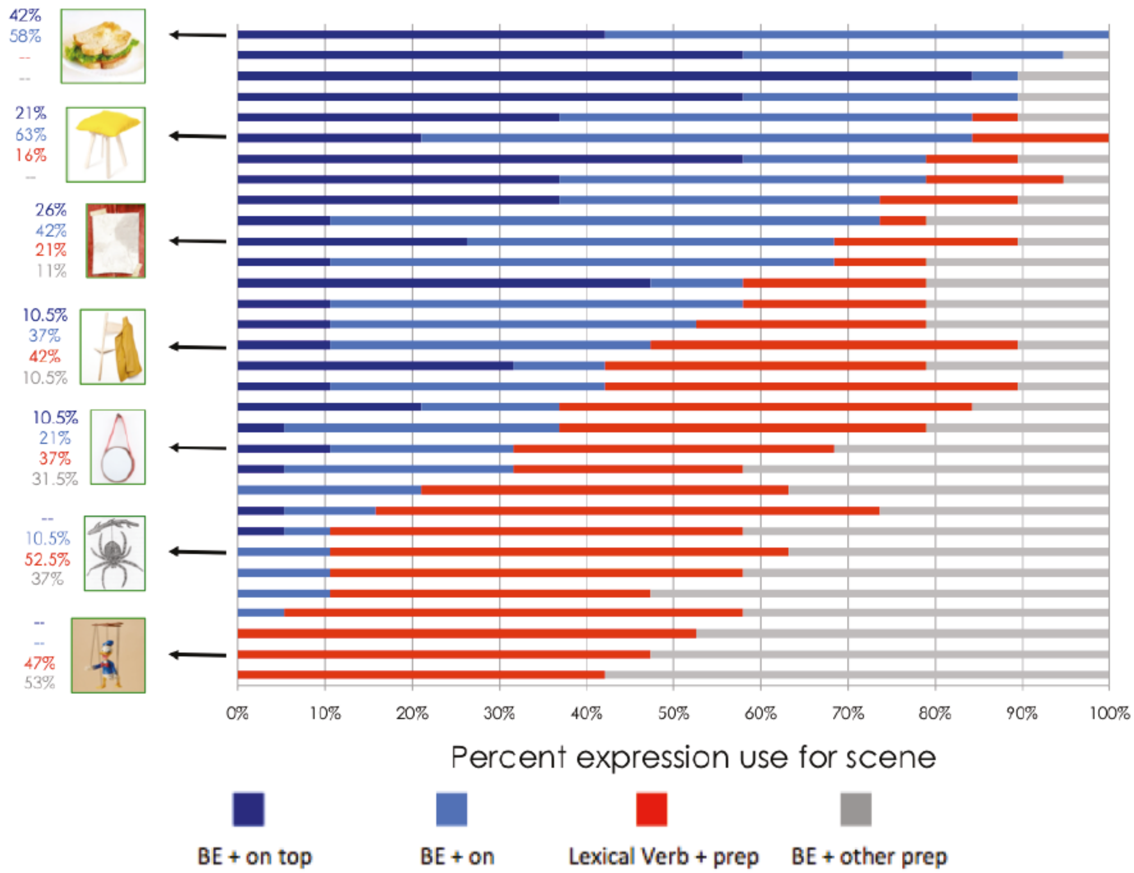


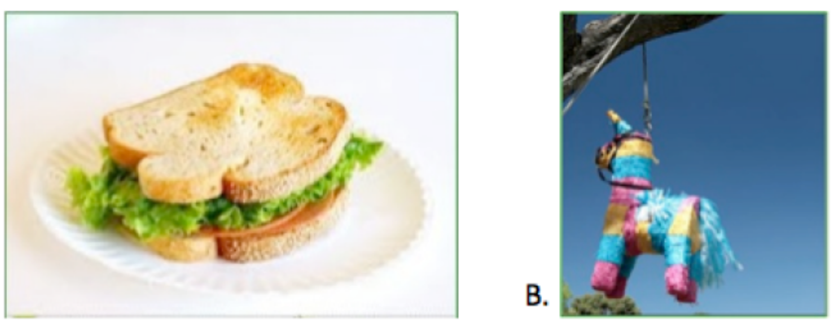
Figure 19. Distribution of main expression types for Support descriptions across a subset of the 64 items. Individual items are on y-axis; percent use for different expressions is on x-axis.

Table 3. Multinomial model summary with correlations between model-fitted values and observed expression use.

	BE + on top	*BE + on (top)*	*Lexical verb + preposition*	*BE + other preposition*
Intercept	**2.14**	**-1.97**	**1.91**	**1.28**
Vertical β	**0.89**	**0.33**	**-0.32**	**-0.27**
Surface match β	**0.23**	**0.52**	**-0.58**	**-0.24**
Control β	**-1.06**	**-0.29**	**0.22**	0.16 *(ns)*
Model fit-observed correlation (*r*)	0.71	0.81	0.78	0.64

Adults' use of [BE + on top] and [BE + on (top)] is positively predicted by Vertical and Surface ratings and negatively predicted by Control ratings

Vertical and Surface ratings, together, positively predicted the use of both *is on top* ($r = 0.71$) and *is on (top)* ($r = 0.81$). Items in which all of the figure object was above the ground object (high Vertical rating) and which had a high degree of Surface contact between the two objects, as in Figure 20-A, were most likely to be described using these expressions, especially *is on top*. The model-fitted probability of using these expressions further increased when the item was rated low on Control. This seemingly unintuitive relationship is likely related to the relatively high Control ratings that subjects assigned to items that were rated low on both Vertical position and Surface match: items like the example in Figure 20-B have mechanisms that ensure Control that, critically, are not related to the geometric features. Support items, in contrast to Containment items, feature a wide range of mechanisms for Control that do not depend on Vertical position or Surface match.



A. B.

Figure 20. Items rated high (A) and low (B) on the combination of Vertical and Surface were respectively more or less likely to be described with the expression *is on (top)*.

Adults' use of [lexical verb + preposition] is negatively predicted by Vertical and Surface ratings and positively predicted by Control ratings

Vertical and Surface ratings, together, negatively predict the use of lexical verb expressions (e.g., *hang from*): items with low Vertical and Surface ratings are most likely to be encoded with a lexical verb. Furthermore, the probability of using a lexical verb is predicted to increase if the item is also rated high on the feature of Control ($r = 0.78$). These expressions were most likely to be used for items in which the no part of the figure object is above the ground object and which had very little contact between object surfaces, but in which the figure was still under Locational Control by the ground object through some other mechanism (Figure 21-A).

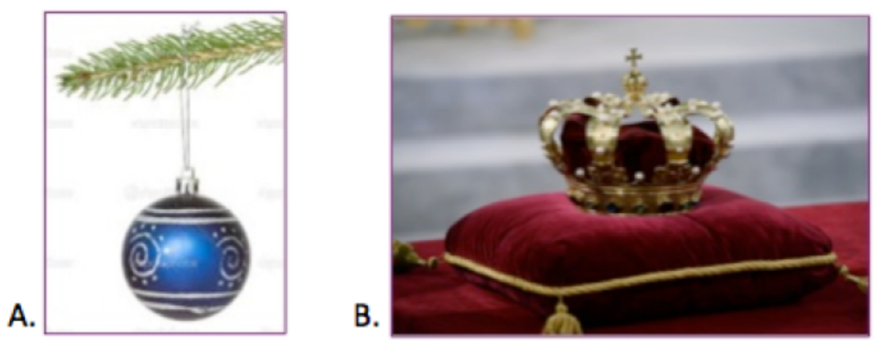


Figure 21. Items rated low (A) and high (B) on the combination of Vertical and Surface were respectively more or less likely to be described with lexical verb expressions or with *BE +other preposition*. The probability of using a lexical verb further increased if the item was also rated high on Control.

Adults' use of [BE +other preposition] is negatively predicted by Vertical and Surface ratings

Vertical and Surface ratings, together, negatively predict the use of *BE + other preposition* (e.g., *is below/near/*under; r = 0.64). These expressions were most likely to be used for items in which the no part of the figure object is above the ground object and which had very little contact between object surfaces (see again, Figure 21-A).

Discussion.

The variation in a small number of geometric and functional features predicted variation in speaker's production of the four different types of spatial expressions in encoding both Containment and Support relations. For both Containment and Support relations, all three features played a role in determining the joint distribution of spatial expressions over the items. Interestingly, features combined in different ways to predict different types of expressions. Spatial expressions like *BE + in(side)* were positively related to geometric and functional features – as the values of these features increased, the likelihood of using these Containment (*BE + in(side)*) increased (Figure 10). For Support, however, (*BE + on (top)*) expressions increased as the values of geometric features increased and the value of the functional feature (Control) *decreased*. Lexical verb expressions, on the other hand, bore negative relationships to geometric feature values – as the feature values decreased, the likelihood of using a lexical verb expression increased (Figures 17 and 21).

Experiment 3: Relationships between non-relational object features and spatial expression use

Experiments 1 and 2 established strong relationships between a small set of geometric and functional features and speakers' variation in the use of a range of spatial expressions. These features were *relational* in nature: they encoded aspects of the relationship between both the figure and ground objects in the item. However, it may be that the relationship between spatial language and a feature space is inevitable, given any feature of objects, relational or not, that varies over the sample of items in the study. Thus, Experiment 3 served as a control, testing the feature-language relationship using a set of plausible features that, critically, only applied to one of the two salient objects in the item (and did not encode properties of the relations between objects). Ratings for these non-relational features were collected separately for both the figure and ground objects in each item. The chosen *non-relational* feature for Containment relations was *Degree of curvature*, which has been proposed in past work to contribute to the meaning of the spatial term *in* (see Feist & Gentner, 1998; Lockwood et al. 2005). For Support, I defined the non-relational feature *Degree of horizontal orientation* (simply put, the degree to which an object is aligned with the horizontal plane), which intuitively varies among different Support items in the sample. The question of interest is whether these non-relational, single-object features will predict variation in expression use as successfully as the relational-features did in Experiment 2. I predicted that, by virtue of their insensitivity to relations between objects, single-object features would fail to predict spatial expression use for either Containment or Support relations.

Method

Participants were a new set of 40 adults recruited from the JHU internal experimental subject pool and participated through an online interface for course credit. Each participant was randomly assigned to provide feature ratings for either the 64 Containment items (N=20; 8 males) or the 64 Support items (N=20; 9 males) used in Experiments 1 and 2.

Table 4. Rating prompts and scales provided to subjects in single-object feature rating task for Containment (top) and Support (bottom) items.

Containment Feature	**Rating prompt**	**Scale endpoints [4…1]**
Curvature (Object A)	*How curved is Object A?*	A has a high degree of curvature A is relatively flat
Curvature (Object B)	*How curved is Object B?*	B has a high degree of curvature B is relatively flat
Support Feature	**Rating prompt**	**Scale endpoints [4…1]**
Horizontal Orientation (Object A)	*How is Object A situated in the HORIZONTAL and VERTICAL dimensions?*	A is well-aligned with the HORIZONTAL dimension A is well-aligned with the VERTICAL dimension
Horizontal Orientation (Object B)	*How is Object B situated in the HORIZONTAL and VERTICAL dimensions?*	B is well-aligned with the HORIZONTAL dimension B is well-aligned with the VERTICAL dimension

Results.

Each of the 20 participants provided ratings on each of the two features for all 64 Containment or Support items. Ratings were then aggregated across participants, as in Experiment 1, and analyzed separately for Containment and Support relations.

Participants consistently rated all 64 Containment items on the Curvature of both the figure object (Object A) and the ground object (Object B), and all 64 Support items on the Horizontal Orientation of both objects[6]. However, these ratings did not directly predict language use from Experiment 2 and did not reliably correlate with features, from Experiment 1, that were predictive of language use. The correlations between model-fitted values and observed language use are presented in Table 5 for the best-fitting non-relational feature models alongside the original best-fitting relational feature models from Experiment 2. It should be apparent that, even where the non-relational feature-language correlations are

[6] Participants' ratings of single-object features for both Containment and Support relations showed the same or lower degree of variability compared to Experiment 1 participants' ratings of geometric features, suggesting high agreement in both rating tasks.

statistically reliable, they do not approach the strength of the relational feature-language correlations.

Table 5. Comparison of correlation between model-fitted values and observed language use for best-fitting non-relational feature models (Experiment 3) vs. best-fitting relational feature models (Experiment 2).

Containment expressions	**Best-fitting non-relational feature model correlations (Exp 3)**	**Best-fitting relational feature model correlations (Exp 2)**
BE + inside	0.32	0.68
BE + in(side)	0.29	0.67
lexical V + prep	0.29	0.63
BE + prep	0.25 (ns)	0.63
Support expressions	**Best-fitting non-relational feature model correlations (Exp 3)**	**Best-fitting relational feature model correlations (Exp 2)**
BE + on top	0.40	0.71
BE + on (top)	0.24 (ns)	0.81
lexical V + prep	0.34	0.79
BE + prep	0.069 (ns)	0.64

Discussion

The single-object features tested in Experiment 3 were plausible features and, in fact, have been previously proposed as influences on the use of *in* and *on* in English (Feist & Gentner, 1998; Feist, 2000, 2004) and discussed as contributing to the meanings of spatial terms in other languages. However, these features failed to reliably predict the use of any spatial expressions across the set of Containment and Support items and did not correlate with the features that were predictive of language use from Experiment 2. One salient difference between these single-object features and the features from Experiments 1 and 2 is that the latter feature set critically encodes properties of *relations between* objects, not just properties of objects themselves. Arguably, spatial terms like *is in/on* are most sensitive to this kind of relational information when encoding object configurations.

Study 1 Summary and Interim Conclusions

Study 1 experimentally validates geometric and functional feature space across two large and diverse relation sets: Containment, which I propose is geometrically structured by degree of Enclosure and degree of Volume match (tightness of fit), and Support, geometrically structured by Vertical position and degree of Surface match (contact between surfaces). I also hypothesized that both relational sets should vary with respect to a functional feature – Locational Control – but had no predictions about how values for this feature would vary across items. Feature ratings from a group of naïve adults validated the hypothesized organization of items across the geometric feature dimensions and, similarly, adults' consistent ratings of Control supported the prediction that items should vary, in some way, along this functional feature dimension.

Experiment 2 revealed that variation in geometric and functional features of relations is related to variation in the use of different types of spatial expressions. The best fitting models of expression use revealed that the use of different expressions across items is strongly and reliably predicted by different combinations of geometric and functional features across items. Experiment 3 showed that this relationship does not hold for a plausible set of non-relational features (i.e., features that apply to one object or another, but not to the relation between the objects): variation in this set of non-relational features is unrelated to the systematic variation in speakers' spatial expression choice. Thus, the organization of adults' language-relevant semantic space is tied to a specific type of feature – one that encodes properties of the relation between two objects, not simply spatial information about one object, such as its concavity or absolute horizontal/vertical position. The corpus of descriptions showed considerable variability in the proportion of *is in* and *is on* expressions used across items, contrasting with the standard data reduction employed by previous approaches (i.e., measuring only the modal response for each item). To the extent that this variability can be traced to a relatively small number of conceptual factors, these results represent empirical and theoretical progress.

Taken together, the findings from Experiments 1-3 support the following interim conclusions:

- There is a structured semantic space underlying the use of spatial expressions by mature (adult) speakers.
- This space is consistently organized by a small number of geometric features: Enclosure and Volume Match for Containment, Vertical position and Surface Match for Support. Items with high ratings on these features were increasingly likely to be encoded with *BE + in(side)* (Containment) and *BE + on (top)* (Support).
- Additionally, the functional feature of Locational Control factored in adults' use of different expression types for both Containment and Support. However, this feature differed in its predictive relationship to Containment and Support expressions, specifically *BE + in(side)* and *BE + on (top)*. Containment items rated high on Control were more likely to be encoded by *BE + in(side)*, whereas Support items rated high on Control were *less* likely to be encoded with *BE + on(top)*.

There is an open question about whether the meanings – i.e., the truth-conditional semantics – of expressions like *BE + in/on* are sensitive to the same fine-grained variation in geometric and functional features. To address the potential difference between expression meaning and expression use, I compared the patterns of production of *BE + in/on* with truth value judgment patterns for the same items. The detailed methods and results of this truth value judgment measure are reported in the Appendix. With the exception of 3 Containment items and 2 Support items, judged “true” by less than 75% of participants, truth value judgments were close to ceiling, despite substantial variation in the probability with which *BE + in/on* was used to encode these items. Thus, production of these expressions reflects more fine-grained differences between items then the basic semantics of *BE + in/on* would lead one to expect.

Chapter 3

Study 2: How does the development of spatial feature knowledge influence the development of spatial language?

Study 1 established relationships between geometric and functional features of Containment and Support relations, rated by adults, and the patterns of spatial expression use produced by adults. However, the adults in Study 1 presumably have a great deal of exposure to object configurations and are experts in their language. In Study 2, I extend the examination of feature knowledge and spatial encoding to young children, asking both about children's early knowledge of spatial features and the developing relationship between features and spatial expression use. The experiments in Study 2 are structured similar to the adult experiments of Study 1, except that, where relevant, I have the opportunity to also compare child and adult feature knowledge and language use.

Study 2 proceeds as follows: first, I examine a set of feature ratings from 6 year-old children (Experiment 4) parallel to the adult feature ratings in Study 1, Experiment 1. These child ratings are compared to adult rating data from Study 1 and evaluated for internal consistency and covariance. Following this, I report sets of spatial language descriptions from 4 year-olds and 6 year-olds (Experiment 5) and compare them to the adult descriptions from Study 1. Finally, I examine the relationships between children's feature knowledge and their spatial expression use (Experiment 6). I investigate the ways in which these relationships are similar to and different from adult feature-language relationships.

These data will be revisited again in Study 3, where I consider the additional role of parental spatial language input in the developing spatial language profile for children.

Experiment 4: Establishing a geometric and functional feature space for children

Experiment 4 yields a baseline measure of children's knowledge of geometric and functional features for the same scenes that adults rated in Study 1. While I expect children's ratings to include more noise, overall, than adults' ratings, there are a few developmental patterns that could arise. One possible developmental difference is in children's consistency in rating the functional feature Control – the locational control that one object has over another – since this feature depends heavily on knowledge of object properties and functions, which children may not fully possess. Conversely, I expect children to show adult-like sensitivity to geometric features like Enclosure and Vertical Position, since these are properties of object configurations that are perceptually available for evaluation (i.e., they do not require inferences about hidden properties or functions of objects) and that infants show sensitivity to pre-linguistically (Hespos & Baillargeon, 2001a, 2001b, 2006; Hespos & Spelke, 2004, 2007).

Method.

Twenty children, ages 5;11-7;0 (Mean age = 6;5, 11 males) participated in the study. Each child was randomly assigned to provide feature ratings for the set of 64 Containment or 64 Support items used in Study 1[7].

Ratings were collected using the same online interface used for adults in Experiment 1 with two modifications aimed at making the task more accessible to children. First, the task was presented on an iPad touch screen interface (guided by the experimenter) that allowed children to indicate their rating by pressing a location on the display instead of maneuvering a mouse. Example Containment and Support rating trials are displayed in Figures 22 and 23,

[7] Eight images from Experiment 1 were replaced with new scenes that either had better image resolution (3 scenes) or objects that were easier for children to identify/name (5 scenes).

respectively. Second, the task was prefaced by 6 training trials to ensure that children understood the feature dimension under evaluation. Two training items were chosen for each feature and were designed to be unambiguous examples of a high and low rating for that feature, illustrating the endpoints of each feature rating scale.

Object A: strawberries
Object B: plastic bag

8. Let's talk about moving!

If I move B, do you think A will...

definitely move with it	probably move with it	maybe move with it	probably won't move with it

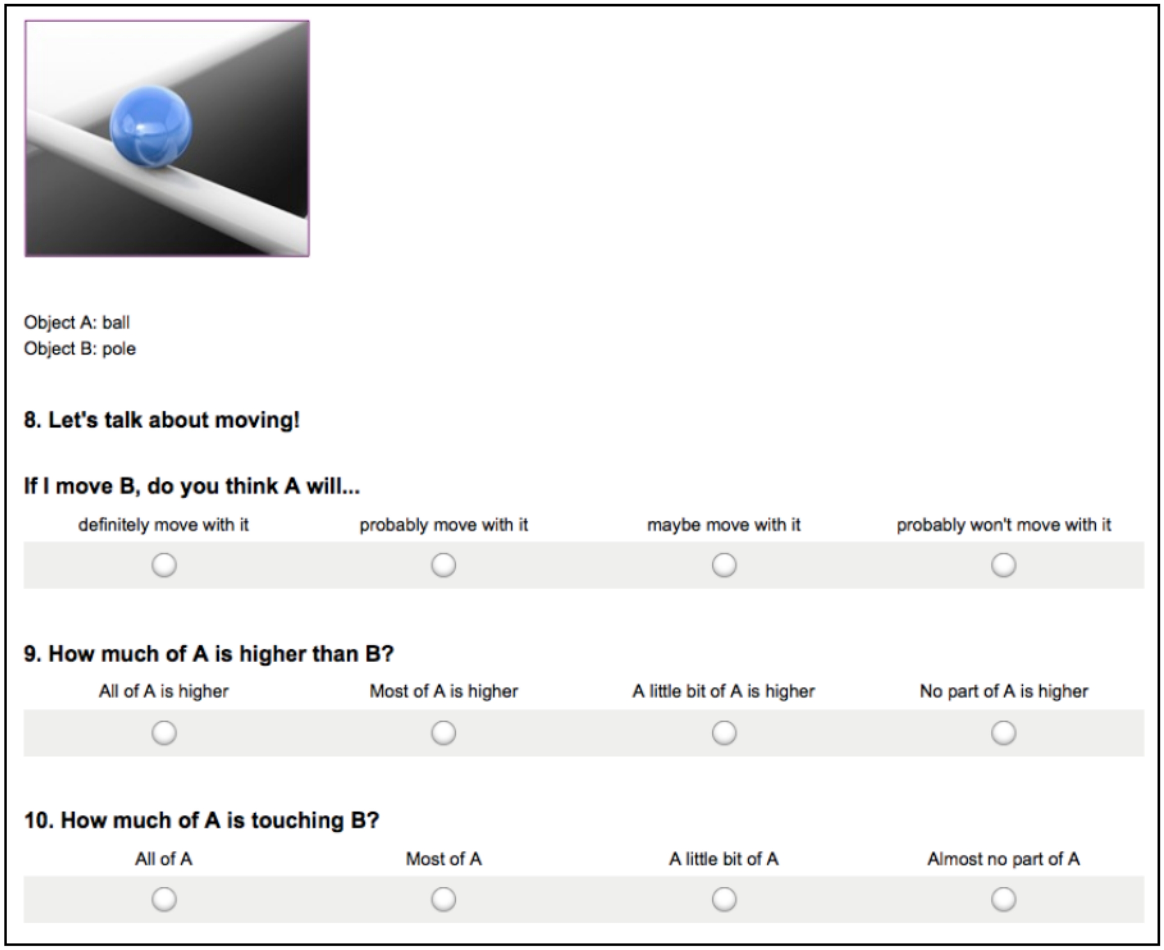
9. Is B...

All around A	Mostly around A	Partly around A	Not really around A

10. Is there...

Lots of empty space	Some empty space	A little empty space	No empty space

Figure 22. Sample Containment feature rating trial for children.


Object A: ball
Object B: pole

8. Let's talk about moving!

If I move B, do you think A will...

definitely move with it	probably move with it	maybe move with it	probably won't move with it
○	○	○	○

9. How much of A is higher than B?

All of A is higher	Most of A is higher	A little bit of A is higher	No part of A is higher
○	○	○	○

10. How much of A is touching B?

All of A	Most of A	A little bit of A	Almost no part of A
○	○	○	○

Figure 23. Sample Support feature rating trial for children.

Results

Containment features

As in Experiment 1, ratings were elicited for each item for the two geometric features of Containment relations – Enclosure and Volume match – as well as a rating of Control (the degree to which one object controls the location of another).

Analysis 1. Are children's attested geometric and control ratings consistent with adults' ratings of these features?

Geometric feature ratings. Children's geometric feature ratings showed moderate to high correlations with adult ratings from Experiment 1. Children's ratings of Enclosure were highly correlated with adults' (r=0.902), and Volume ratings also showed a moderate correlation between both groups (r=0.506).

Control feature ratings. In contrast to geometric features, children's ratings of Control were not correlated with adults' earlier ratings. This is consistent with the idea that children have incomplete or noisy knowledge of (Locational) Control between objects. One possibility, discussed in detail later, is that adult-like knowledge of Control is tied to sophisticated understanding of objects and variable object-specific properties beyond geometric features like Enclosure (such as material, center of mass/gravity, weight, etc.).

Analysis 2. Are children's attested values of one Containment feature systematically related to their attested values of another feature?

The distribution of all 64 Containment items along the three feature dimensions is shown in Figure 24. Similar to adults, correlations between children's Enclosure and Volume ratings were low (r=0.109). Correlations between children's Control ratings and Enclosure ratings (r=0.198) were also low but reliable, as were correlations between Control and Volume ratings (r=0.261). Children's feature ratings have a covariance structure among feature dimensions that is similar to adults' ratings, but show weaker correlations between features.

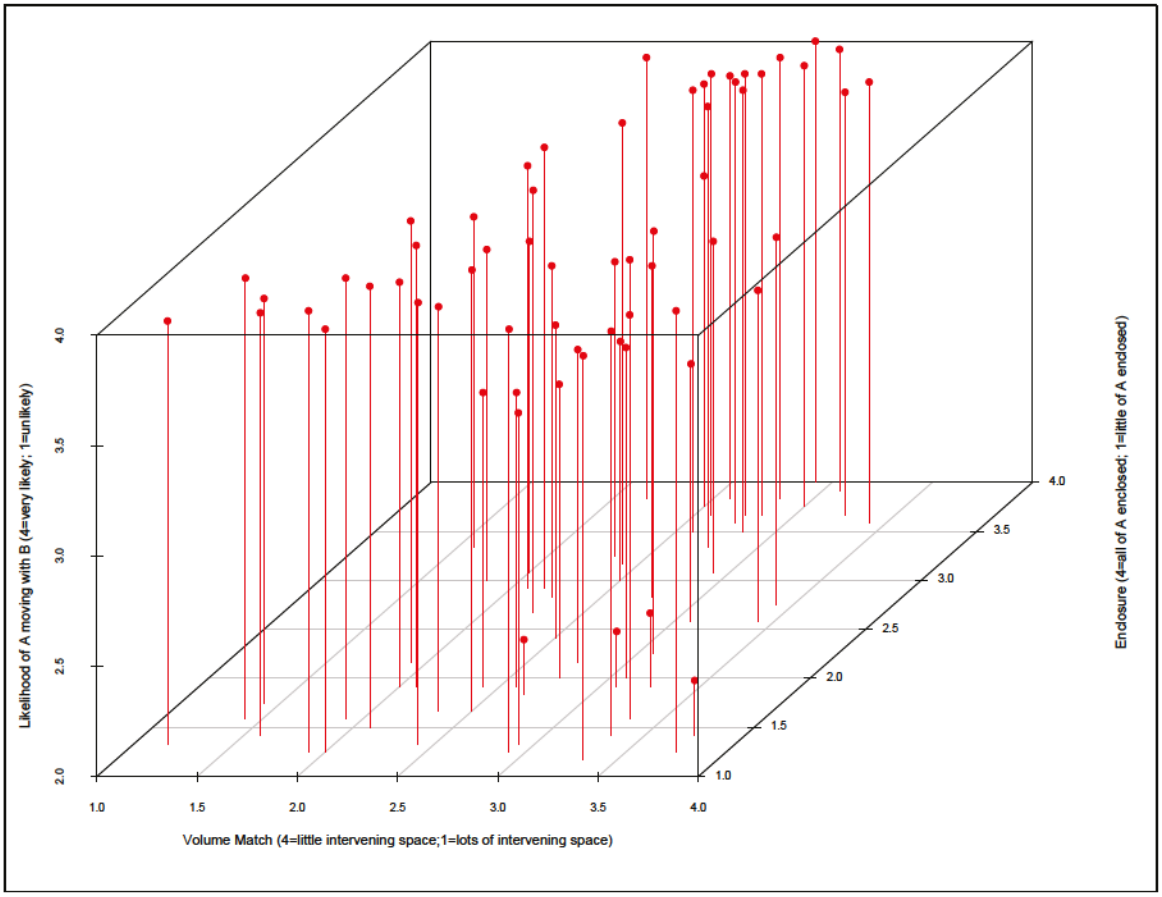


Figure 24. Distribution of children's ratings for Containment items along three feature dimensions: Volume match (x-axis), Enclosure (y-axis), and Control (z-axis).

Support features

For each Support item, I elicited ratings for two geometric features – Vertical position and Surface match – as well as a rating of Control between the two objects.

Analysis 1. Are children's attested geometric and control ratings consistent with adults' ratings of these features?

Geometric feature ratings. Children's geometric feature ratings were highly correlated with adults' ratings from Experiment 1. Children and adults showed strong positive correlations in their ratings of both Vertical position (r=0.931) and Surface match (0.863).

Control feature ratings. Unlike in Containment, children's ratings of Control for Support relations were moderately correlated with adults' ratings (r=0.558).

Analysis 2. Are children's attested values of one Support feature systematically related to their attested values of another feature?

Figure 25 shows the distribution of all 64 Support items along the three feature dimensions. Similar to adults, children's Vertical and Surface ratings were moderately correlated across items (r = 0.516): children rated relations in which the figure object was below the ground object as also having very little surface contact. Vertical ratings were also moderately correlated with Control ratings (r =0.384), suggesting that the relative vertical positions of objects factored into children's judgments about the control of one object by the other. As with adults, children's Surface ratings were not reliably correlated with Control ratings (r=0.047, *ns*).

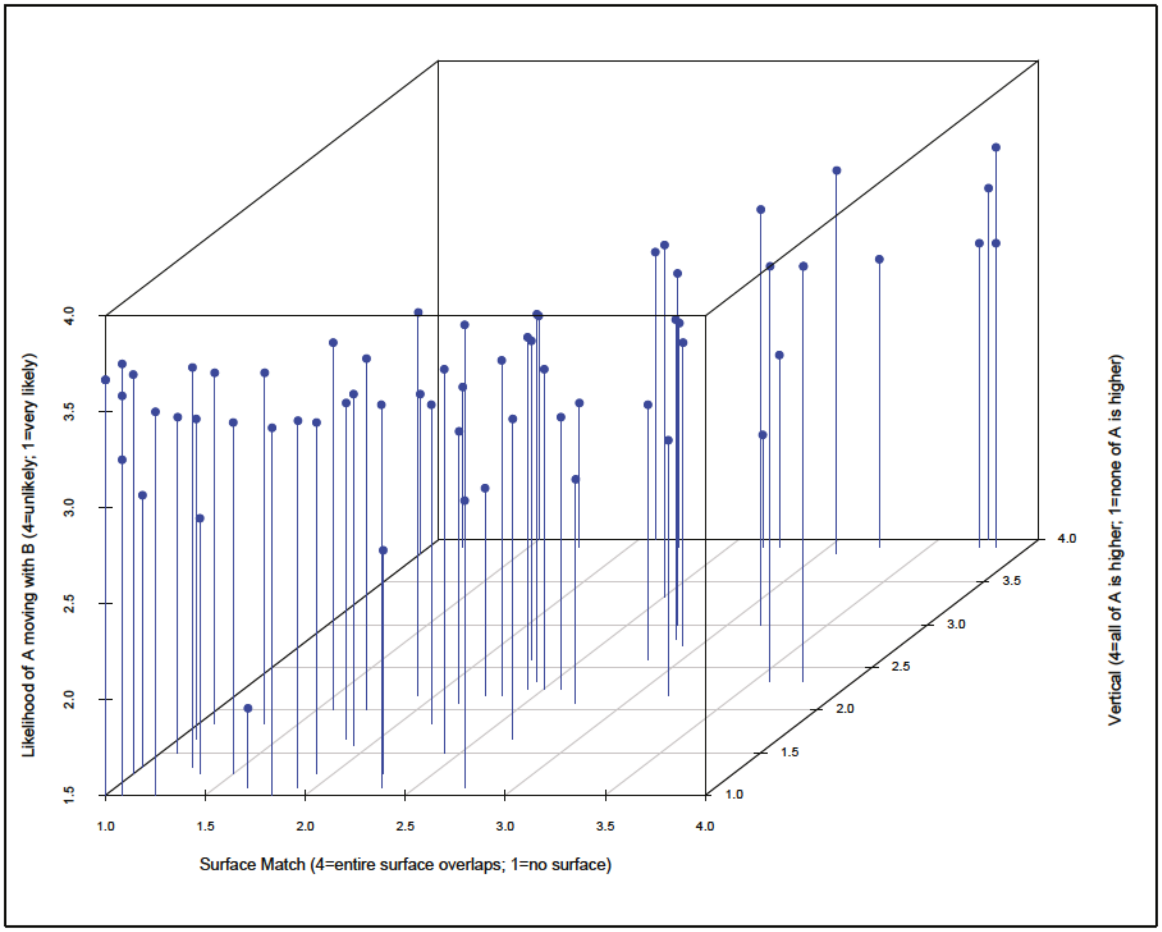


Figure 25. Distribution of children's ratings for Support items along three feature dimensions: Surface match (x-axis), Vertical position (y-axis), and Control (z-axis).

Discussion.

The results of Experiment 4 demonstrate that children and adults have similar distributions of geometric feature values across items, and suggest that children are able to consistently judge at least some features of spatial relations. The places in which children and adults differ are their ratings of Control for both Containment and, to a lesser degree, Support relations. Children's and adults' Control ratings are uncorrelated for Containment and moderately correlated for Support; in both cases, correlations between child and adult ratings are much weaker for Control than for geometric features.

Children and adults also show similar covariance among geometric features and between geometric features and Control. However, correlations between children's geometric feature ratings and Control ratings are weaker than adults' correlations for both Containment and Support.

Experiment 5: Comparing child and adult spatial language use

In Experiment 5, I compare the distribution of spatial expressions produced by adults (Experiment 2), to a new set of production data from 4- and 6-year-old children, looking for systematic changes in spatial expression use over development. Previous studies of spatial language acquisition (Johannes et al., in prep; Landau et al., under review) show that children use far fewer complex expressions, lexical verb expressions, than adults. The results of Experiment 5 are consistent with this age difference.

Method.

Twelve young children, ages 4;0-4;10 (Mean age = 4;5, 5 males) and 12 older children, ages 6;1-6;10 (Mean age = 6;6, 5 males) participated. Each child was asked to describe the 64 Containment scenes and the 64 Support scenes, presented in pseudorandom order. I used the same elicitation method as in Study 1 Experiment 2, with two slight modifications. First, children received two practice scenes to describe; these scenes elicit terms other than the ones typically used to encode Containment and Support (e.g., *beside, next to, above*). Second, items were presented to children by the experimenter as a Powerpoint presentation on a laptop computer. The experimenter labeled each object (to establish that the child was familiar with the label) before prompting a spatial description with the question "Where is the [labeled figure object]?"

Results.

Children's spatial descriptions were transcribed and coded for one of four types of spatial expression: *BE + inside/on top, BE + in(side)/on(top)*, *lexical verb + preposition*, *BE + other preposition*. I first report correlations across ages for each expression type and then examine changes in the use of each type across development. These analyses are conducted separately for Containment and Support items.

Containment expression use

Analysis 1: Similarities in Containment expression use across development

Figure 26 shows 4-year-olds' (Fig. 26-A), 6-year-olds (Fig. 26-B), and adults' (Fig. 26-C) distributions of each of the four expression types for a subset of Containment items. Additionally, Table 6 gives a detailed breakdown of expression use across the three age groups for 8 example Containment items. Expressions used by 4-year-olds, 6-year-olds, and adults were similarly distributed across items. All three age groups used *BE + in/inside* (at least once) to encode each item and used lexical verbs and other prepositions to encode similar sets of items.

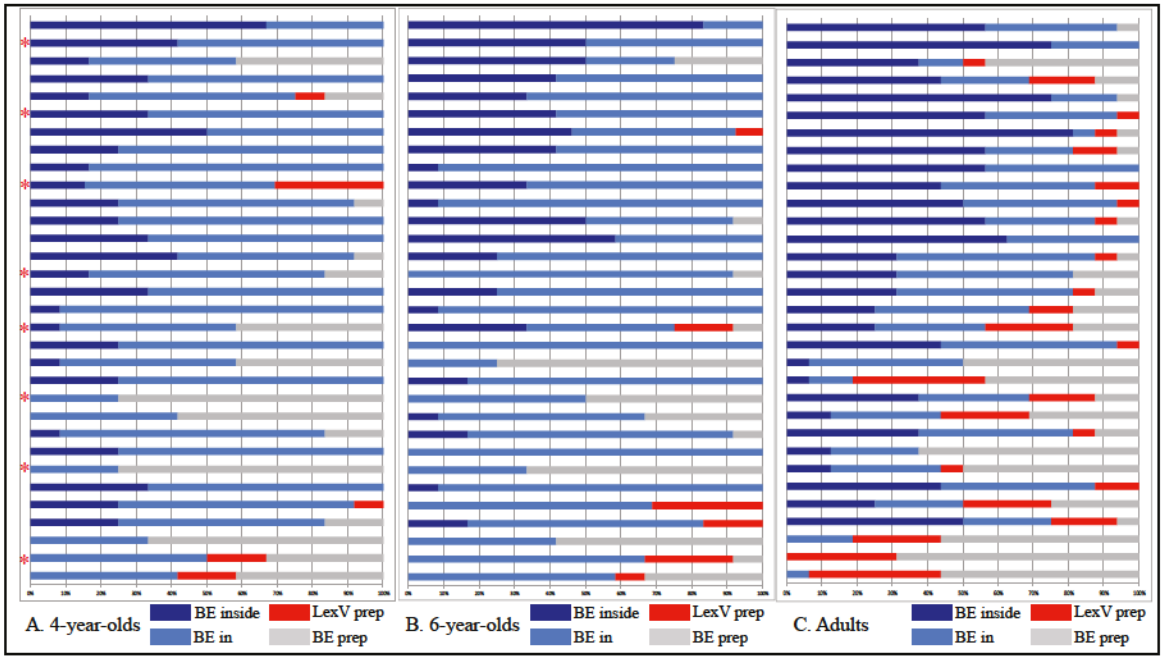


Figure 26. Distribution of each of the four expression types across a subset (32/64) of Containment items for A. 4-year-olds, B. 6-year-olds, and C. Adults. The presence of a "*" symbol indicates example items that are later described in more detail.

Table 6. Proportion of each expression type used by each age group to describe example Containment items (indicted by "*" in Figure 26).

	BE inside			BE in			BE in(side)			LexV + preposition			BE + preposition		
	4-yrs	6-yrs	adult	4-yrs	6-yrs	adult	4-yrs	6-yrs	adult	4-yrs	6-yrs	adult	4-yrs	6-yrs	adult
	0.42	0.5	0.75	0.58	0.5	0.25	1	1	1	--	--	--	--	--	--
	0.33	0.42	0.56	0.67	0.58	0.38	1	1	0.94	--	--	0.06	--	--	--
	0.16	0.33	0.44	0.51	0.67	0.44	0.67	1	0.88	0.33	--	0.12	--	--	--
	0.42	0.25	0.32	0.5	0.75	0.56	0.92	1	0.88	--	--	0.06	0.08	--	0.06
	0.08	0.33	0.25	0.5	0.42	0.31	0.58	0.75	0.56	--	0.17	0.25	0.42	0.08	0.19
	--	--	0.37	0.25	0.5	0.31	0.25	0.5	0.68	--	--	0.19	0.75	0.5	0.13
	--	--	0.13	0.25	0.33	0.31	0.25	0.33	0.44	--	--	0.06	0.75	0.67	0.5
	--	--	--	0.5	0.67	--	0.5	0.67	--	0.17	0.25	0.32	0.33	0.08	0.68

The rate of use of a particular expression type across Containment scenes was also reliably correlated across age groups (Table 7). Correlations between all age groups were strongest for *BE + inside* and *BE + in(side)* expressions, with coefficients (Pearson's r) ranging from r=0.67 to r=0.85. Overall, correlations between 4- and 6-year-olds' expressions were strongest, and adults' expression use showed correlations of similar strength for both 4- and 6-year-olds.

Table 7. Correlation coefficients (Pearson's R) for relationships between Containment expression use for pairs of age groups. All correlations significant at p<.05.

Adults' correlations with	BE inside	BE in(side)	LexV + preposition	BE + other preposition
6-year-olds	0.71	0.67	0.47	0.62
4-year-olds	0.70	0.69	0.37	0.65
6-year-olds' correlations with	BE inside	BE in(side)	LexV + preposition	BE + other preposition
4-year-olds	0.80	0.85	0.47	0.83

Analysis 2: Changes in Containment expression use over development

A series of mixed effects logistic regression analyses were used to measure differences in Containment expression use across age groups: one model for each expression type. Each model featured Subject and Item as random effects on the intercept and Age group as the only fixed effect. For each expression type, the Age predictor compared adults to 6-year-olds and adults to 4-year-olds in order to determine points of difference between adults and children of a particular age.

Across items, adults used *BE + inside* at greater rates compared to 4-year-olds (β = 1.69, p <.05), but not 6-year-olds. However, adults used *BE + in(side)* at lower rates compared to both 4-year-olds (β = 0.977, p <.01) and 6-year-olds (β = 1.40, p <.01). This was the only expression type for which adults and 6-year-olds differed and was driven by differences in adults' and children's use of *BE + in*. Adults used lexical verb expressions at greater rates compared to 4-year-olds (β = 1.87, p <.01), but not 6-year-olds. Finally, there were no reliable age differences in the use of *BE + preposition* expressions across Containment items.

Support expression use

Analysis 1: Similarities in Support expression use across development

Figure 27 shows 4-year-olds' (Fig. 27-A), 6-year-olds (Fig. 27-B), and adults' (Fig. 27-C) distributions of each of the four expression types for a subset of Support items. Table 6 gives a breakdown of expression use across the three age groups for 8 example Support items. On the whole, expressions were similarly distributed across items. All three age groups made use of all four of the expression types and used the same expression types to encode similar sets of items, albeit at different rates.

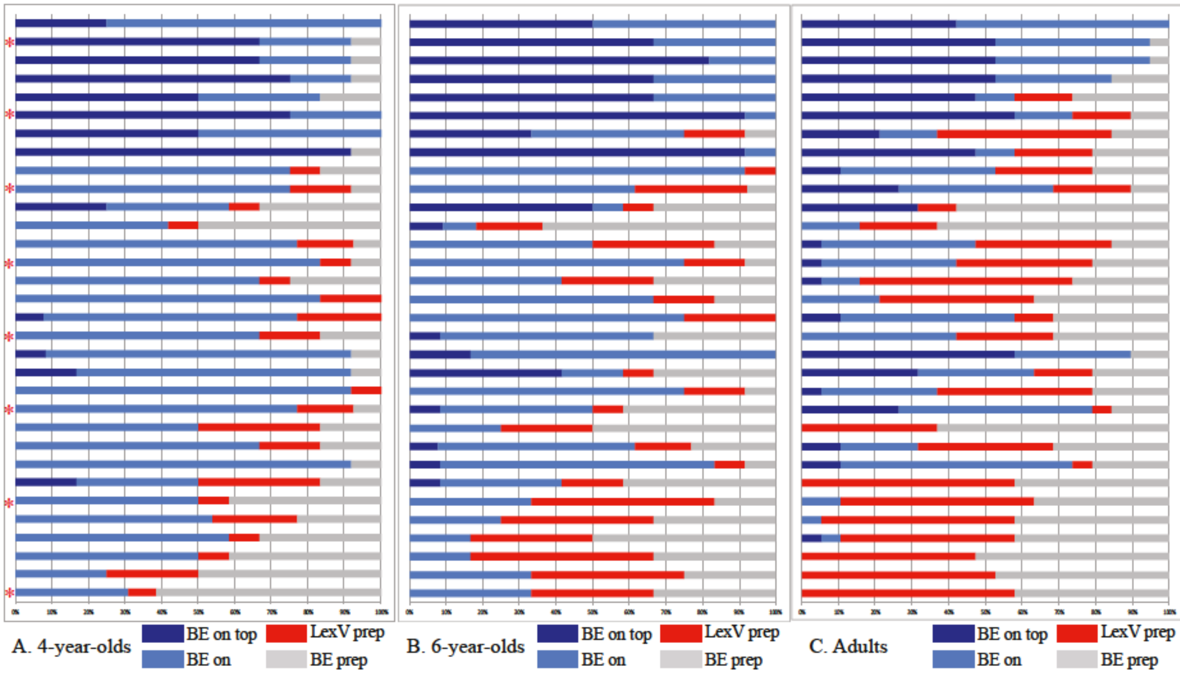
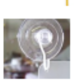


Figure 27. Distribution of each of the four expression types across a subset (32/64) of Support items for A. 4-year-olds, B. 6-year-olds, and C. Adults. The presence of a "*" symbol indicates example items that are later described in more detail.

Table 8. Proportion of each expression type used by each age group to describe example Support items (indicted by "*" in Figure 27).

	BE on top			BE on			BE on (top)			LexV + preposition			BE + preposition		
	4-yrs	6-yrs	adult	4-yrs	6-yrs	adult	4-yrs	6-yrs	adult	4-yrs	6-yrs	adult	4-yrs	6-yrs	adult
	0.67	0.67	0.53	0.25	0.33	0.42	0.92	1	0.95	--	--	--	0.08	--	0.05
	0.75	0.92	0.58	0.25	0.08	0.16	1	1	0.74	--	--	0.16	--	--	0.10
	--	--	0.26	0.75	0.62	0.42	0.75	0.62	0.68	0.17	0.30	0.21	0.08	0.08	0.11
	--	--	0.05	0.83	0.75	0.37	0.83	0.75	0.42	0.08	0.17	0.37	0.09	0.08	0.21
	--	0.08	--	0.67	0.58	0.42	0.67	0.66	0.42	0.17	--	0.26	0.17	0.34	0.32
	--	0.08	0.26	0.83	0.42	0.53	0.83	0.5	0.79	0.17	0.08	0.05	0.10	0.42	0.16
	--	--	--	0.5	0.33	0.11	0.5	0.33	0.11	0.08	0.5	0.52	0.72	0.17	0.37
	--	--	--	0.33	0.33	--	0.33	0.33	--	0.08	0.33	0.58	0.67	0.34	0.42

The rate of use of a particular expression type across Support scenes was also reliably correlated across age groups (Table 9). Correlations between all age groups were strongest for *BE + on top* and *BE + on (top)* expressions, with coefficients (Pearson's r) ranging from r=0.70 to r=0.93.

Table 9. Correlations (Pearson's R) between each pair of age groups for each Support expression type. All correlations significant at p<.05.

Adults' correlations with	BE on top	BE on (top)	LexV + preposition	BE + other preposition
6-year-olds	0.88	0.77	0.62	0.70
4-year-olds	0.81	0.70	0.44	0.59
6-year-olds' correlations with	BE on top	BE on (top)	LexV + preposition	BE + other preposition
4-year-olds	0.93	0.73	0.60	0.57

Analysis 2: Changes in Support expression use over development

As in Containment, age-based differences in Support expression use were measured using a series of mixed effects logistic regression analyses with Subject and Item as random effects on the intercept and Age group as the only fixed effect. For each expression type, an initial *a priori* model was fit using a set of contrasts that first compared adults to children (6- and 4-year-olds combined) and then compared 6-year-olds to 4-year-olds, followed by a post hoc model comparing adults to 6-year-olds and adults to 4-year-olds. The results of these pairs of models are summarized for each expression type below.

There were no reliable age differences in the use of *BE + on top* expressions across items. However, adults used *BE + on (top)* at lower rates than both 4-year-olds (β = 1.89, p

<.01) and 6-year-olds ($\beta = 1.22$, $p <.01$)[8]. There were also no reliable age differences in the use of lexical verb expressions across items. However, the difference between 4-year-olds and adults' use of lexical verb expressions trended towards statistical significance ($\beta = 1.35$, $p =.07$), with adults using lexical verbs at numerically higher rates. Finally, as in Containment, there were no reliable age differences in the use of *BE + preposition* expressions across items.

Discussion.

Adults, 6-year-olds, and 4-year-olds use expressions in similar ways across Containment and Support items, showing reliable correlations in their rates and patterns of use for all four of the expression types. However, regression analyses also revealed systematic developmental differences in the use of different types of Containment and Support expressions. Though these analyses are relatively coarse-grained, the results suggest developmental continuity in changes in expression use. Adults and 4-year-olds differed in their use of *BE + inside, BE + in(side),* and lexical verb expressions for Containment, while adults and 6-year-olds only differed in their use of *BE + in(side).* Likewise, for Support, adults and 4-year-olds differed in their use of *BE +on (top)* and lexical verb expressions, while adults and 6-year-olds only differed in *BE + on (top)* use.

Experiment 6: Relating geometric and functional features to children's spatial expression use

In Experiment 6, I evaluated the relationships between geometric and functional features, rated by both children and adults, and children's rates of use of different expression

[8] Additionally, post hoc analyses revealed that 4-year-olds used *BE + on (top)* at numerically higher rates than 6-year-olds, and this difference trended towards statistical significance ($\beta = 0.34$, $p =.07$).

types for encoding Containment and Support items. As in the case of adult feature-language relationships, modeled in Study 1 Experiment 2, I used mixed effects multinomial regression models to predict children's joint use of each of the four expression types as a function of ratings of geometric and functional features. In these models, Subject and Item served as random effects on the intercept of the regression equation, and each of the three features (two geometric, one functional) are included as fixed effect predictors. Below, I report significant feature predictors for the best fitting model for an expression type, and, as a measure of fit, report correlations between model-fitted values across items and children's observed rates of expression use for those items.

The primary models that I computed use (6-year-old) children's feature ratings, reviewed in Experiment 4, to predict patterns of 4-year-old expression use and 6-year-old expression use. However, there is a possibility that the children in Experiment 4 have not yet developed the ability to consistently judge certain features of Containment and Support relations. For example, the functional feature Control varies on the basis of many different properties of objects, such as material or center of gravity and, as such, might be difficult for children to explicitly judge, though might still be predictive of their choice of spatial expressions. Therefore, I computed additional models of 4- and 6-year-old expression use as a function of adult feature ratings. For each expression type, I report child feature models of child expression use followed by the matching adult feature models of child expression use (e.g., 4-year-old expression use predicted by child feature ratings and 4-year-old expression use predicted by adult feature ratings). I also include the results from Study 1, Experiment 2 models predicting adult expression use with adult feature ratings to serve as a comparison.

Results.

Containment feature-language relationships

The multinomial models used here predict the joint use of all four types of expressions. That is, the model predicts the full corpus of expressions, grouped by type, produced by children in each age group. For ease of understanding, however, I organize and report the results of these models by expression type for the four types below:

(5) BE + inside (e.g., A *is inside* B)

(6) BE + in or inside (e.g., A *is in(side)* B)

(7) Lexical Verb + Preposition (e.g., A *is held by* B)

(8) BE + Other Preposition (e.g., A *is near* B)

Using only the statistically significant predictors, I calculate predicted rates of expression use (by item) and compute correlations between these model-fitted values and the observed rates of expression use (also by item). These correlations give a measure of how strongly the weighted combination of features in a model relates to expression use.

[BE + inside] and *[BE + in(side)]*. Children's ratings of geometric features were the best predictors of 4- and 6-year-olds' use of *BE +inside* (Table 10). Four-year-old usage was predicted solely by Enclosure, with higher ratings predicting greater probability of *BE +inside* use. Six-year-olds' usage was predicted by a combination of Enclosure and Volume match, with higher ratings of both geometric features predicting greater probability of *BE + inside* (Figure 28). This feature-language relationship was similar for children's use of *BE +in(side)* (Table 11), for which both 4- and 6-year-olds' usage was predicted solely by

Enclosure ratings (see also Figure 28). As in adult feature-language models, the relationship between Enclosure and language use was stronger for *BE +inside* compared to *BE +in(side)*. However, unlike adults, children's use of these expressions was not predicted by ratings of Control.

Table 10. Best-fitting model coefficients for model intercept and Enclosure, Volume, and Control feature predictors and correlation between model-fitted values and observed rates of use of *BE + inside*. Unless indicated, all values are significant at $p<.05$.

Use of: *BE + inside*	(Exp. 2) Adult language/adult feature models	4-year-old expression use predicted by		6-year-old expression use predicted by	
		Child ratings	Adult ratings	Child ratings	Adult ratings
Intercept	**-1.68**	**-3.74**	**-3.50**	**-5.89**	**-5.20**
Enclosure β	**0.84**	**0.66**	**0.79**	**1.09**	**1.25**
Volume β	-0.05 (*ns*)	0.31 (*ns*)	0.18 (*ns*)	**0.48**	0.10 (*ns*)
Control β	**0.68**	-0.02 (*ns*)	-0.32 (*ns*)	0.25 (*ns*)	0.05 (*ns*)
Predicted-actual *r*	0.68	0.74	0.64	0.84	0.67

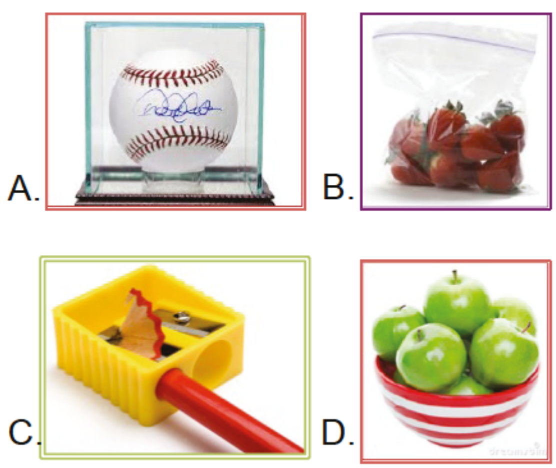


Figure 28. Items rated high (A, B), and low (C, D) on Enclosure were respectively more and less likely to be described with the expressions *BE + inside* and *BE +in(side)* by children.

Table 11. Best-fitting model coefficients for model intercept and Enclosure, Volume, and Control feature predictors and correlation between model-fitted values and observed rates of use of *BE + in(side)*. Unless indicated, all values are significant at $p<.05$.

Use of: *BE + in(side)*	(Exp. 2) Adult language/adult feature models	4-year-old expression use predicted by		6-year-old expression use predicted by	
		Child ratings	Adult ratings	Child ratings	Adult ratings
Intercept	**-1.78**	**0.98**	**0.66**	**0.94**	**0.82**
Enclosure β	**0.47**	**0.19**	**0.26**	**0.18**	**0.24**
Volume β	0.02 (*ns*)	0.03 (*ns*)	0.06 (*ns*)	0.07 (*ns*)	0.04 (*ns*)
Control β	**0.48**	-0.24 (*ns*)	-0.11 (*ns*)	-0.08 (*ns*)	-0.03 (*ns*)
Model fit-observed *r*	0.67	0.58	0.55	0.61	0.54

[Lexical verb + preposition]. Children's use of lexical verbs at each age (Table 12) was predicted by different combinations of adult and child feature ratings. Model-fitted values for 4-year-old lexical verb use did not reliably correlate with 4-year-olds' actual verb use and this was true for both models with child feature ratings and adult feature ratings. Child and adult ratings lead to different feature combinations predicting 6-year-olds' lexical verb use. Using child ratings, lexical verb use was predicted by both geometric features: 6-year-olds were predicted to use lexical verbs for items rated low on Enclosure and Volume match (Figure 29). Models using adult ratings, however, predict only that 6-year-olds will use lexical verbs for items rated low on Control. Adult usage, by comparison, was best predicted by a combination of both geometric features and Control.

Table 12. Best-fitting model coefficients for model intercept and Enclosure, Volume, and Control feature predictors and correlation between model-fitted values and observed rates of use of *lexical verb + preposition*. Unless indicated, all values are significant at $p<.05$.

Use of: *Lex verb + preposition*	(Exp. 2) Adult language/adult feature models	4-year-old expression use predicted by		6-year-old expression use predicted by	
		Child ratings	Adult ratings	Child ratings	Adult ratings
Intercept	**3.48**	-0.87 (*ns*)	0.73 (*ns*)	**3.94**	-0.07 (*ns*)
Enclosure β	**-0.70**	0.26 (*ns*)	-0.45 (*ns*)	**-1.22**	-0.11 (*ns*)
Volume β	**-1.05**	**-1.50**	-0.37 (*ns*)	**-1.54**	0.09 (*ns*)
Control β	**-0.49**	**3.56**	0.18 (*ns*)	1.17 (*ns*)	**-0.68**
Model fit-observed *r*	0.63	0.25 (*ns*)	0.22 (*ns*)	0.55	0.45

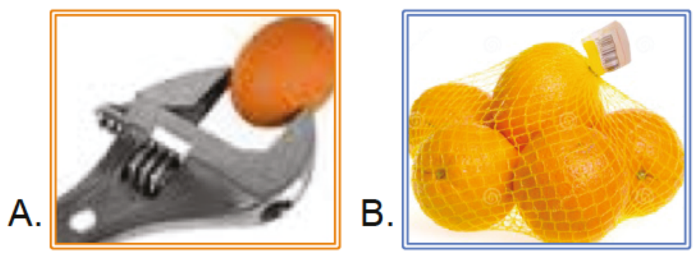


Figure 29. Items rated low (A) and high (B) on Enclosure and Volume match were respectively more and less likely to be described with lexical verb expressions by 6-year-olds, but not 4-year-olds (who showed no reliable feature-language relationships).

[BE + other preposition]. Children's use of *BE +other preposition* (Table 13) was predicted primarily by Enclosure ratings: children were most likely to use *BE + other preposition* for items with low Enclosure ratings (Figure 30). Four-year-olds' usage was additionally predicted by Control ratings – the combination of low Enclosure and high Control ratings predicted greater probability of *BE + other preposition* use – but this relationship was only reliable for child ratings and the direction of the relationship between Control and 4-year-olds' usage was opposite to the relationship between Control and adults' usage.

Table 13. Best-fitting (log-odds) model coefficients for model intercept and Enclosure, Volume, and Control feature predictors and correlation between model-fitted values and observed rates of use of *BE + other preposition*. Unless indicated, all values are significant at p<.05.

Use of: *BE +other preposition*	(Exp. 2) Adult language/adult feature models	4-year-old expression use predicted by		6-year-old expression use predicted by	
		Child ratings	Adult ratings	Child ratings	Adult ratings
Intercept	**3.27**	0.76 (*ns*)	**3.29**	**1.56**	**2.66**
Enclosure β	**-1.20**	**-1.21**	**-1.50**	**-1.27**	**-1.61**
Volume β	0.01 (*ns*)	0.17 (*ns*)	-0.18 (*ns*)	-0.01 (*ns*)	0.07 (*ns*)
Control β	**-1.13**	**0.89**	0.30 (*ns*)	-0.01 (*ns*)	0.04 (*ns*)
Model fit-observed r	0.63	0.49	0.53	0.53	0.42

A.  B. 

Figure 30. Items rated low (A) and high (B) on Enclosure were respectively more and less likely to be described with *BE + other preposition* by children.

Thus, for Containment items, children showed adult-like relationships between geometric features and expression use, specifically *BE + inside* and *BE + in(side)*. However, neither 4- nor 6-year-olds' use of these expressions was predicted by Control ratings. Similarly, Control was not consistently related to children's use of lexical verb expressions, for which only 6-year-olds showed adult-like geometric feature relationships, or to their use of *BE + other preposition* expressions, for which both ages showed adult-like relationships between Enclosure and *BE + preposition* use.

Support feature-language relationships

As in the case of Containment, I organize and report the results of these models by expression type for the four types of Support expressions below:

(1) BE + on top (e.g., A *is on top of* B)

(2) BE + on or on top (e.g., A *is on (top of)* B)

(3) Lexical Verb + Preposition (e.g., A *is hanging from* B)

(4) BE + Other Preposition (e.g., A *is under* B)

Model-fitted values are calculated using only the statistically significant predictors. Correlations between these model-fitted values and the observed rates of expression use serve as a measure of how strongly the weighted combination of features in a model relates to expression use.

[BE + on top]. Children's use of *BE + on top* (Table 14) was predicted by a combination of Vertical position and Control ratings: high ratings of Vertical position and Control predicted greater probability of using *BE + on top* for both 4- and 6-year-olds (Figure 31). This relationship held for both child and adult ratings. Adults' usage was additionally sensitive to Surface ratings.

Table 14. Best-fitting model coefficients for model intercept and Vertical, Surface, and Control feature predictors and correlation between model-fitted values and observed rates of use of *BE + on top*. Unless indicated, all values are significant at $p<.05$.

Use of: *BE + on top*	(Exp. 2) Adult language/adult feature models	4-year-old expression use predicted by		6-year-old expression use predicted by	
		Child ratings	Adult ratings	Child ratings	Adult ratings
Intercept	**2.14**	**-3.32**	0.48 (*ns*)	-0.83 (*ns*)	1.50 (*ns*)
Vertical β	**0.90**	**1.91**	**1.52**	**1.62**	**1.14**
Surface β	**0.23**	-0.06 (*ns*)	-0.18 (*ns*)	0.09 (*ns*)	-0.04 (*ns*)
Control β	**-1.06**	**-1.03**	**-1.98**	**-1.04**	**-1.55**
Model fit-observed r	0.71	0.89	0.78	0.80	0.79

Figure 31. Items rated high on Vertical position and low on Control (A, B) were more likely to be described with the expressions *BE + on top* by children. The opposite was true of items rated low on Vertical position and high on Control (C, D).

[BE + on (top)]. Children's use of *BE + on (top)* (Table 15) was predicted in different ways by adult and child ratings. For 6-year-olds, *BE + on (top)* use was predicted by adult ratings with the same combination of all three features used to predict adult usage. Both adults and 6-year-olds were predicted to use *BE +on (top)* for items rated high on Vertical position and Surface match but rated low on Control (Figure 32). As in the adult feature models, items that are rated low on geometric features are often rated high on Control due to the presence of different mechanisms (being stuck to or attached to an object) that ensure support and locational control in the absence of support from below. Four-year-olds' use was weakly predicted by adult Control ratings and was not reliably related to any child ratings.

Table 15. Best-fitting model coefficients for model intercept and Vertical, Surface, and Control feature predictors and correlation between model-fitted values and observed rates of use of *BE + on (top)*. Unless indicated, all values are significant at $p<.05$.

Use of: *BE + on (top)*	(Exp. 2) Adult language/adult feature models	4-year-old expression use predicted by		6-year-old expression use predicted by	
		Child ratings	Adult ratings	Child ratings	Adult ratings
Intercept	**-1.96**	**1.65**	**1.73**	0.60 (*ns*)	**1.28**
Vertical β	**0.33**	0.08 (*ns*)	0.05 (*ns*)	**0.26**	**0.18**
Surface β	**0.52**	0.08 (*ns*)	0.06 (*ns*)	0.11 (*ns*)	**0.17**
Control β	**-0.28**	-0.17 (*ns*)	**-0.12**	-0.04 (*ns*)	**-0.25**
Model fit-observed *r*	0.80	0.53	0.54	0.69	0.76

Figure 32. Items rated high on Vertical position and Surface match, but low on Control (A) were more likely to be described with the expressions *BE + on (top)* by 6-year-old children (4-year-olds did not show a systematic relationship). The opposite was true of items rated low on Vertical position and Surface match but high on Control (B).

[Lexical verb + preposition]. Children's use of lexical verbs at each age (Table 16) was predicted by different combinations of child and adult features. For models using child ratings, 4- and 6-year-olds' lexical verb use was predicted by the same combination of Vertical position and Surface match features: children were predicted to use lexical verbs at greatest rates for items that were rated low on both Vertical position and Surface match

(Figure 33). Using adult ratings, however, 6-year-olds' use was predicted by the same combinations of both geometric features and Control as adults, while 4-year-olds' lexical verb use was only predicted by adult ratings of Vertical position. The comparable fit between 6-year-olds' lexical verb use and different combinations of child and adult features ratings underscores the idea that 6-year-olds' patterns of language use are intermediate between those of young (4-year-old) children and adults.

Table 16. Best-fitting model coefficients for model intercept and Vertical, Surface, and Control feature predictors and correlation between model-fitted values and observed rates of use of *lexical verb + preposition*. Unless indicated, all values are significant at $p<.05$.

Use of: *Lex verb + preposition*	(Exp. 2) Adult language/adult feature models	4-year-old expression use predicted by		6-year-old expression use predicted by	
		Child ratings	Adult ratings	Child ratings	Adult ratings
Intercept	**1.92**	0.06 (*ns*)	-0.07 (*ns*)	0.17 (*ns*)	-0.34 (*ns*)
Vertical β	**-0.32**	**-0.48**	**-0.68**	**-0.57**	**-0.47**
Surface β	**-0.58**	**-0.38**	-0.11 (*ns*)	**-0.33**	**-0.57**
Control β	**0.22**	-0.01 (*ns*)	0.09 (*ns*)	0.32 (*ns*)	**0.39**
Model fit-observed *r*	0.78	0.50	0.56	0.71	0.70

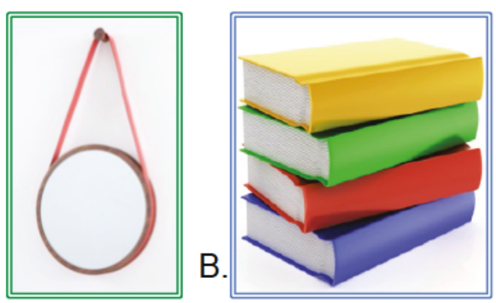
A.
B.


Figure 33. Items rated low on Vertical position and Surface match (A) were more likely to be described with the expressions *BE + on (top)* by children. The opposite was true of items rated low on Vertical position and Surface (B).

[BE + other preposition]. Children's use of *BE + other preposition* at each age (Table 17) was predicted by different combinations of child and adult features. For models using child ratings, 4- and 6-year-olds' *BE + other preposition* use was predicted by the different

combinations of Vertical position and Surface match features: 6-year-olds were predicted to use *BE + other preposition* at greatest rates for items that were rated low on both Vertical position and Surface match (Figure 34), but 4-year-olds' usage was predicted to be greatest for items that were rated *high* on Vertical position and low on Surface match. Neither group of children aligned with the combinations of adult ratings that predicted adult usage of *BE + other preposition*. One possible reason for these highly variable relationships is that children, like adults, use *BE +other preposition* to encode a relation other than Support (for example, general proximity via *near*, position on an axis via *above, below, over, under*, etc.) and any systematic relationships between these other prepositions and the three features measured would depend on the particular prepositions used, which may differ somewhat idiosyncratically by subject.

Table 17. Best-fitting model coefficients for model intercept and Vertical, Surface, and Control feature predictors and correlation between model-fitted values and observed rates of use of *BE + other preposition*. Unless indicated, all values are significant at $p<.05$.

Use of: *BE +other preposition*	(Exp. 2) Adult language/adult feature models	4-year-old expression use predicted by		6-year-old expression use predicted by	
		Child ratings	Adult ratings	Child ratings	Adult ratings
Intercept	**1.28**	0.76 (*ns*)	**-3.15**	1.48 (*ns*)	**-1.69**
Vertical β	**-0.27**	**0.89**	0.13 (*ns*)	**-0.44**	**-0.29**
Surface β	**-0.24**	**-1.21**	-0.21 (*ns*)	**-0.11**	-0.03 (*ns*)
Control β	0.16 (*ns*)	0.17 (*ns*)	**0.67**	-0.25 (*ns*)	**0.43**
Model fit-observed *r*	0.64	0.49	0.32	0.56	0.57

A. B.

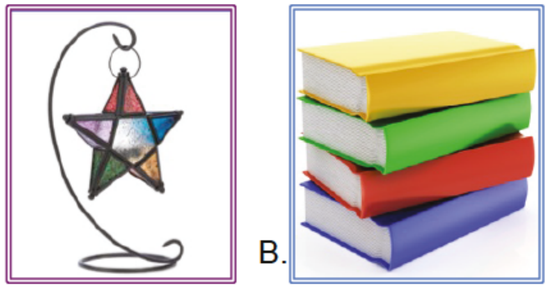


Figure 34. Items rated low on Vertical position and Surface match (A) were more likely to be described with *BE + preposition* by 6-year-old children (the same relationship did not hold for 4-year-olds). The opposite was true of items rated high on Vertical position and Surface (B).

Discussion.

Four- and 6-year-olds' spatial expression use was reliably predicted by models that used child ratings (with correlations between model fit and observed values between 0.25 and 0.84) and by models that used adult ratings (with correlations between 0.22 and 0.79). In Containment models, children and adults showed similar relationships between geometric feature ratings and spatial expression use, but children's expression use was not reliably predicted by their ratings of Control in the way that adult expression use in Study 1 was. For Support models, children and adults showed similar feature predictors (including Control) for *BE +on top*, but the use of all other expressions was predicted by different combinations of features for children and adults. One exception to this was 6-year-olds' use of lexical verbs, which showed adult-like relationships to adult feature ratings (i.e., with lexical verbs predicted by low ratings on both geometric features and high Control ratings).

Study 2 Summary and Interim Conclusions

Study 2 explores the development of geometric and functional feature knowledge and its relationship to children's spatial expression use. In Experiment 4, 6-year-old children provided ratings of Containment items on the geometric features Enclosure and Volume match, and rated Support items on Vertical position and Surface match. Children also provided ratings of Control for both Containment and Support items. Experiment 5 measured 4- and 6-year-olds' use of different expression types and Experiment 6 related children's and adults' feature ratings to children's use of different expressions.

The findings from Experiments 4-6 yield a number of interim conclusions about spatial language development:

- Children, like adults, provide consistent ratings of geometric features and Locational Control. Although children's geometric ratings are strongly correlated with adults' geometric ratings, children's ratings of Control are only moderately correlated with adults' Control ratings. This suggests that children have adult-like knowledge of geometric features, but have not acquired complete knowledge of functional relationships that underlie understanding of Control.
- Also like adults, children systematically vary in their use of different types of expressions across Containment and Support items. As they grow older, children's patterns of expression use increasingly resemble those of adults: there are fewer differences between usage patterns for 6-year-olds and adults compared to 4-year-olds and adults.
- Despite general similarity in feature ratings and expression use, children and adults differ in the feature combinations that underlie their spatial expression use. In general, children show adult-like relationships between geometric features and expression use, especially for expressions like *BE + inside/on top*.
- Children's use of lexical verbs and *BE + other preposition* expressions, however, is not consistently related to their ratings of geometric features or Control. In the case of

lexical verbs, this inconsistency may be tied to children's growing understanding of (non-geometric) mechanisms of Containment and Support. For *BE +other prepositions*, however, children are likely conceptualizing object configurations in a wide variety of ways, evidenced by their use of a wide range of prepositions (e.g., *near, beside, under, above,* etc.).

The results of Study 2 invite questions about how children acquire adult-like feature-language relationships. One possibility is that in order to fully understand a functional feature like Control children must learn a great deal of information about particular objects and their functional affordances. Another, slightly different, perspective is that children may use other kinds of knowledge to scaffold the acquisition of spatial language in the absence of complete knowledge of functional features. I explore this second possibility in Study 3, where I examine the role of parent input in children's spatial language use.

Chapter 4

Study 3: How does input influence the development of spatial language?

Study 2 demonstrated that although child adult spatial language is correlated, there are also systematic age differences in the use of specific expressions. Furthermore, for some expressions, different combinations of geometric and functional features predict children and adults' respective patterns of use. Specifically, children's use of lexical verbs and *BE + other prepositions* is not predicted by the same feature combinations that reliably predict adult usage, and, in particular, does not systematically relate to ratings of the functional feature Control in the way that adult language does.

These differences open the door to questions about how these language feature relationships develop over the course of language acquisition. The possibility that I pursue in Study 3 is that (parent) input provides scaffolding for the early mapping between features of spatial relations and the language that encodes them. Study 3 addresses the role of parent input in the spatial language profiles and, specifically, how this input mediates the relationships between geometric and functional features and child spatial language. I measure the input environment of each child from Study 2 by asking his or her parents to directly estimate their likelihood of using different types of spatial expressions when describing spatial scenes to their child. Critically, these scenes are identical to the scenes that children in Study 2 (and adults, in Study 1) are asked to describe, and parent and child data are collected together as parent-child dyads providing unique estimates of spatial language input for individual children in the sample. These data can be brought to bear on a number of questions through the use of several types of analyses, described in Experiments 7 and 8 below.

Experiment 7: Preliminary relationships between parent input estimates and child and adult spatial language

In Experiment 7, I relate self-reported parent estimates of spatial expression input to the patterns of spatial expressions produced by adults (Study 1) and 4- and 6-year-old children (Study 2). There is no existing work examining how parents' child-directed spatial expression use aligns with both the expression use of adults (i.e., non-child-directed) and children, especially for the diverse sample of relations tested here. While child corpus data (from e.g., CHILDES; MacWhinney, 2000) provide a coarse estimate of child and parent speech, the conditions under which children and parents produce these spatial expressions are highly variable and rarely reflect targeted encoding of static spatial relations. The data reported here are optimal in that they provide fine-grained measures of child and parent language use for exactly the sets of spatial relations that are modeled by feature ratings in Studies 1 and 2.

Method.

Participants were parents of the 12 4-year-olds and 12 6-year-olds from Study 2. Each parent was presented with all 64 Containment items and 64 Support items, in random order, within a self-paced computerized rating task. On each trial, parents were given a single item with objects labeled and were asked to indicate how likely they are to use each of five different expressions when describing the spatial relation to their child. Parents indicated their response through radial buttons; an example trial is given in Figure 35 below.

Object A: dart
Object B: dartboard

17. Please think about describing the scene above to your child. How likely are you use each of the following sentences to describe the relationship between Object A and Object B in the scene?

	Extremely likely	Very likely	Somewhat likely	Not likely	Extremely unlikely
A is in B					
A is inside of B					
A is in the middle of B					
A is stuck in B					
A is sticking out of B					
Other (specify below)					

Other (please specify)

Figure 35. Example trial for parent input rating task.

Five different descriptions were chosen for each scene by selecting the most frequent expressions from the corpus of adult spatial expressions that fit into five different types of constructions, as in Table 18 below, along with an option to specify other expressions not listed. The set of construction types was designed to systematically combine different verb types – copular verbs vs. lexical verbs — with different prepositions –prepositions *in* and *on*, their specialized counterparts *inside* and *on top of*, and other prepositions (above, below, to, from, etc.).

Table 18. Example expressions, by type, for parent input survey.

Construction	Containment example	Support example
BE + in/on	A is in B	A is on B
BE + inside/on top	A is inside of B	A is on top of B
BE + other prep	A is in the middle of B	A is over B
Lexical verb + in/on	A is stuck in B	A is resting on B
Lexical verb + other prep	A is sticking out of B	A is hanging from B

Results.

The analyses reported here (in Experiment 7) establish the degree to which variation in parents' input patterns across items was correlated with variation in children's spatial description patterns. Correlations were computed over average parent input patterns and average usage patterns from adults, 4-year-olds, and 6-year-olds. As a result, this preliminary set of results does not reflect the relationship between an individual child's expression use and the input estimates made by her parent; I examine this relationship in Experiment 8.

Parents' self-reported input was measured using 5-point a scale from "Extremely likely" to "Extremely unlikely". Responses for each item were coded to yield a numerical rating, from 1 to 5, for each expression type. In order to align the expression types used for parent input tasks with the types measured for adult and child language, two additional input expression types were calculated[9]. First, *BE + in(side)* and *BE +on (top)* input estimates were calculated for Containment and Support items, respectively, by selecting the best rating (i.e., the rating that reflected parents' increased likelihood) from the estimates of *BE + in/on* and *BE + inside/on top*. Second, *lexical verb + preposition* input estimates were calculated

[9] In both cases, additional coarser expression types were computed (instead of e.g., coding production data in a more fine-grained way) because the data that resulted from the original coding were too sparse to yield reliably correlations between input estimates and expression use.

by selecting the best rating from estimates of *lexical verb + in/on* and *lexical verb +other preposition*[10].

Parent input estimates for Containment items

Table 19 shows several sets of correlations for Containment items. First, correlations between parent input estimates for each age group (that is, the correlation between parents of 4-year-olds and parents of 6-year-olds); then, correlations between estimates of parent input (for both parents of 4-year-olds and parents of 6-year-olds) and adult expression use. And, finally, the table shows correlations between estimates of parent input and children's expression use – correlating input estimates from parents of 4-year-olds with expression use from 4-year-olds and parents of 6-year-olds with 6-year-olds.

Table 19. Correlations between parent input estimates for Containment relations and correlations between input and child (4- and 6-year-olds) and adult expression use for parents of 4- and 6-year-olds. All correlations are statistically significant at $p<.05$.

Correlations between:	Parents of each age	Parents and adults		Parents and children	
		Parents of 4s	Parents of 6s	4-year-olds	6-year-olds
BE + inside	0.93	0.79	0.86	0.74	0.75
BE + in(side)	0.54	0.50	0.79	0.55	0.89
Lexical V + preposition	0.89	0.70	0.60	0.46	0.40
BE + other preposition	0.82	0.60	0.49	0.63	0.50

[10] This method for collapsing expression types was similar to the method for coding *BE + in(side)* and *BE +on (top)* in child and adult production data: an expression was coded as e.g., *BE +in(side)* if it was either *BE + in* or *BE + inside*.

Parents of 4-year-olds and parents of 6-year-olds were highly correlated in their estimates of use of *BE + inside, lexical verbs*, and *BE +other preposition* expressions across items, but only moderately correlated in their estimates of *BE + in(side)* use. Furthermore, *BE + in(side)* estimates from parents of 6-year-olds were highly correlated with adults' and 6-year-olds' use of *BE + in(side)*, but the same degree of correlation did not hold for estimates from parents of 4-year-olds. This difference in the strength of correlation for Parents of 4-year-olds

Parents' input for both age groups were highly correlated with adults and 4- and 6-year-olds in their use of *BE +inside*, but other expression types were correlated to varying degrees between groups. Correlations between parent input and 4- and 6-year-olds' use of *lexical verbs* and *BE + other preposition* were of particular interest, as children's use of these expressions was not well predicted by child and adult feature ratings. Parents' aggregate input estimates were only moderately correlated with children's use of these expressions, and one possibility, examined in Experiment 8, is that individual parent-child dyads are highly variable in their estimates and use of these expressions. Finally, input estimates from parents of 4- and 6-year-olds showed moderate to high correlations with adults' use of all four of the expression types.

Parent input estimates for Support items

Table 20 shows several sets of correlations for Support items. First, correlations between parent input estimates for each age group (that is, the correlation between parents of 4-year-olds and parents of 6-year-olds); then, correlations between estimates of parent input (for both parents of 4-year-olds and parents of 6-year-olds) and adult expression use. And, finally, the table shows correlations between estimates of parent input and children's expression use – correlating input estimates from parents of 4-year-olds with expression use from 4-year-olds and parents of 6-year-olds with 6-year-olds.

Table 20. Correlations between parent input estimates for Containment relations and correlations between input and child (4- and 6-year-olds) and adult expression use for parents of 4- and 6-year-olds. Correlations are statistically significant at $p<.05$ except where noted (*ns*).

Correlations between:	Parents of each age	Parents and adults		Parents and children	
		Parents of 4s	Parents of 6s	4-year-olds	6-year-olds
BE + on top	0.92	0.79	0.78	0.84	0.89
BE + on (top)	0.87	0.75	0.72	0.63	0.72
Lexical V + preposition	0.61	0.45	0.05 *(ns)*	0.48	0.06 *(ns)*
BE + other preposition	0.72	0.32	0.16 *(ns)*	0.37	0.10 *(ns)*

Parents of 4-year-olds and parents of 6-year-olds were highly correlated in their estimates of use of *BE + on top* and *BE + on (top)* expressions across items, and moderately correlated in their estimates of *lexical verb* use and *BE + other preposition* expressions.

Estimates of *lexical verbs* and *BE + other preposition* use made by parents of 4-year-olds were only weakly correlated with adult and 4-year-olds' use of these expressions (R= 0.32 – 0.48). Estimates of use of these expressions from parents of 6-year-olds were not significantly correlated with either adult or 6-year-old usage. As in the case of Containment, *lexical verb* and *BE + other preposition* expressions were also not well predicted by feature ratings and it is possible that children differences show considerable individual differences in their use of these expressions. Experiment 8 will examine whether these individual differences are mirrored by differences in each parent's estimates of input to their child.

Discussion.

Input estimates from parents of 4- and 6-year-olds were reliably correlated with adult and child language use for some, but not all, types of expressions. For both Containment and Support items, parents' estimates were related to adult and child usage of *BE + inside/on top* and *BE + in(side)/on (top)*. For lexical verb and *BE +other preposition* expressions, however, parent input showed weaker relationships to both adult and child patterns of use. One explanation for this is that parent input is highly variable across individual parents and aggregating input estimates across parents eliminates this variability. In Experiment 8, I address this issue by using individual parent input estimates as predictors of individual child expression use.

Experiment 8: Preliminary relationships between parent input estimates and child and adult spatial language

The hypothesis that I test in Experiment 8 is that parent input bears a predictive relationship to child language in exactly those cases where early knowledge of features does not. That is, children make use of input patterns only when they do not have the requisite conceptual (feature) mapping for a spatial expression. Thus, while parent input might sharpen the feature-language mappings for expressions like *BE + inside/on top*, which are well known by 4- and 6-year-olds, the prediction is that the gains from models that use input in addition to features will be greatest for expressions with lexical verbs and other prepositions (i.e., *BE + other preposition*). Expressions with lexical verbs and other prepositions showed tenuous relationships to geometric and functional features and it is possible that parent input serves as a placeholder or scaffolding for late-developing feature-language relationships.

Results.

Parent input as a predictor of children's Containment expressions

The models reported below were designed by starting with the feature models from Study 2 (Experiment 6) and adding parents' input estimates as an additional predictor. Including parents' estimates of their spatial language input significantly strengthened the correlations between children's observed expression use and the usage patterns predicted by the models. For all but one expression type, parent input estimates served as an additional significant predictor along with the same significant child feature rating predictors found in the best-fitting models from Study 2, Experiment 6. In all cases, including a parent input predictor improved the models' fit to child data and, except where noted, gains in the strength of correlations between model-fitted and observed patterns were statistically reliable (at $p<.01$)[11].

[BE + inside] and *[BE + in(side)]*. Models that included individual parent input in combination with children's ratings of Enclosure significantly improved the correlation between 4- and 6-year-olds observed use of *BE + inside* and *BE + in(side)* and the usage patterns predicted from the significant feature/input predictors alone. For 4-year-olds, the correlation between observed and model-fitted values increased from $r = 0.72$ to $r = 0.82$, for *BE + inside*, and from $r = 0.57$ to $r = 0.67$, for *BE + in(side)*. For 6-year-olds, the strength of correlation increased from $r = 0.84$ to $r = 0.89$, for *BE + inside*, though this increase was not statistically significant, and from $r = 0.61$ to $r = 0.68$, for *BE + in(side)*. Although the gains in

[11] Statistical significance was established using a non-parametric Sign Test on the differences between the differences between fitted and observed values for the feature-only and feature + input models.

correlational strength appear numerically small (increases between 0.05 and 0.1), they are statistically reliable and, in some cases, leave little variance left unaccounted.

[Lexical verb + preposition]. Models that included individual parent input significantly improved the correlation between 4- and 6-year-olds use of lexical verb expressions and the usage patterns predicted from the feature/input predictors alone. The feature-based models for 4-year-olds in Study 2 did not have any reliable feature predictors (only the model intercept) predicting 4-year-olds' lexical verb use. However, parent input was a significant predictor, and including input increased the correlation between observed and predicted data from $r = 0.25$ to $r = 0.47$. For 6-year-olds, the strength of correlation increased from $r = 0.55$ to $r = 0.65$, but the set of feature predictors changed from Enclosure and Volume match to only Enclosure. The change in feature predictors suggests that parent input accounted for a great deal of the variance in expression use that was originally predicted by Volume match ratings.

[BE + other preposition]. Models that included parent input significantly improved the correlation between children's actual and predicted use of *BE + other preposition*. However, for 4-year-olds' parent input itself was not a significant predictor in the best-fitting model. Despite this, the correlation between observed and predicted use of *BE + other preposition* for 4-year-olds increased from $r = 0.48$ to $r = 0.61$. The best fitting model of 6-year-olds' *BE + other preposition* use did include parent input as a significant predictor, along with child Enclosure ratings, and the predicted- observed correlation increased from $r = 0.53$ to $r = 0.66$.

Parent input as a predictor of children's Support expressions

As in Containment, including parents' estimates of their spatial language input significantly strengthened the correlations between children's Support expression use and the usage patterns predicted by the feature ratings models. Unlike in Containment, however, the best-fitting models were based on adult feature ratings[12]. In all cases, including a parent input predictor, in addition to significant adult feature rating predictors, improved the models' fit to child data. Except where noted, increases in the strength of correlations between predicted and observed patterns of use were statistically reliable, with significance established, as in Containment, via a non-parametric Sign test.

[BE + on top]. Models that included parent input significantly improved the correlation between 4- and 6-year-olds use of *BE + on top* and the usage patterns predicted from the feature/input predictors alone. However, these gains were greatest for models with adult feature predictors. For these (adult feature) models, 4- and 6-year-olds' expression use was predicted by a combination of Vertical position and Control (as in Study 2) and parent input. The correlation for 4-year-olds' predicted and observed use increased from $r= 0.78$ to $r=0.89$, and the correlation for 6-year-olds increased from $r= 0.79$ to $r=0.95$.

[BE + on (top)]. Models that included parent input improved the correlation between 4- and 6-year-olds use of *BE + on (top)* and the usage patterns predicted from the (adult)

[12] Including parent input as a predictor aligned children's expression use with adult feature ratings. This was not predicted but is not wholly unexpected: children's and adults' feature ratings often led to equally good (or poor) predictions of children's expression use.

feature/input predictors alone. As in Study 2, 4-year-olds' *BE + on (top)* use was weakly predicted by adult Control ratings. Including input as a predictor increased the correlation between predicted and observed data for 4-year-olds from r= 0.54 to r =0.64. For 6-year-olds, all three features and parent input combined to predict *BE + on (top)* use, increasing the model-fitted and observed correlation from r= 0.69 to r =0.77.

[Lexical verb + preposition]. Models of lexical verb use showed significant increases in the correlation between predicted and observed use for 4-year-olds but not for 6-year-olds. For 4-year-olds, lexical verb use was predicted by (adult) Vertical position ratings along with parent input, and the correlation between predicted and observed data increased from r = 0.56 to r =0.63. As in Study 2, 6-year-olds' lexical verb use was predicted by a combination of all three features, as well as parent input. However, this additional predictor did not result in even a numeric change in the correlation between model-fitted and observed use, which remained at r = 0.70.

[BE + other preposition]. Models that included parent input significantly improved the correlation between 4- and 6-year-olds use of *BE + other preposition* and the model predicted usage patterns. As in Study 2, 4- and 6-year-olds' *BE + other preposition* use was predicted with different combinations of features. For both ages, though, input served as an additional significant predictor of expression use. For 4-year-olds, the combination of Control and parent input increased the predicted-observed correlation for 4-year-olds from r = 0.32 to r =0.64. Likewise, 6-year-olds' fitted- observed correlation increased from r= 0.56

to r =0.66 when input was included in addition to Vertical position and Control, compared to the features alone.

Discussion.

The results of Experiment 8 show that there are numerical and generally significant predictive gains from adding parent input estimates as a predictor in an otherwise feature-based model of child language use. As predicted, these gains were greatest for lexical verb and *BE +other preposition* expressions, which showed weak feature-language relationships in Study 2. For these expressions, gains were also greater for 4-year-olds compared to 6-year-olds, suggesting that younger children may benefit more from, or rely more on, parent input for these and other expressions. Finally, in a few cases, including parent input changed the nature of the feature prediction itself – either removing previously significant feature predictors, or aligning child language with adult features – which was not expected. The second of these two changes is especially interesting: child features were systematically better predictors for Containment, while adult features were better predictors for Support.

Study 3 Summary and Interim Conclusions

Study 2 demonstrated that some expression types (such as BE + inside/on top) were well predicted by child or adult feature ratings, while others (like lexical verbs) showed only weak relationships to features. Building on this finding, Study 3 tested the hypothesis that the information within parent input helps to scaffold weak relationships between features and expression use. Along these lines, the findings from Experiments 7 and 8 can be summarized as follows:

- Adding parent input for individual children to feature-language models strengthened the correlations between model-fitted values and observed expression use across the board for both 4-year-olds and 6-year-olds.
- Predictive gains were greatest for lexical verb expressions and *BE + other preposition* expressions. These results are consistent with the idea the parental input is recruited for the expressions that show weak relationships to features.
- For lexical verbs, weak feature–language relationships may arise from children's limited knowledge of non-geometric mechanisms for Containment or Support. For *BE + other preposition*, feature relationships may be weak to begin with because children (and adults) use a wide range of other prepositions to encode aspects of objects configurations other than the (intended) containment and support relations.
- In one instance (6-year-olds' use of lexical verbs to encode Containment items), including parent input simplified the feature predictors in the model: a model that originally predicted 6-year-olds' lexical verb use as a function of Enclosure and Volume match ratings was replaced by a model that had only Enclosure as a feature predictor (and parent input estimates as an added predictor)[13].
- Finally, the best-fitting feature + input models for children's Containment expression use employed child feature ratings as predictors, while the best models for Support expression use employed adult feature ratings. This difference appears to be driven by the increased accuracy in predicting lexical verb expression use (for 4-year-olds) and *BE + other preposition* use (for 4- and 6-year-olds) and is consistent with the

[13] This is, presumably, a case where one predictor (parent input) largely subsumes the variance that was originally accounted for by another predictor (Volume match). It is unclear whether there is anything theoretically meaningful in this change.

observation that children use these types of expressions more frequently to describe Support items compared to Containment items. Thus, if adult feature ratings provide a better fit for lexical verb and *BE + other expression* use, then they may be the preferred set of predictors in models of children's Support expression use where these expressions are frequently used by children.

I address the general role of parent input in the Conclusion (Chapter 5) below.

Chapter 5

The nature of spatial language encoding

This thesis builds on the work of Johannes, Landau, and colleagues by exploring the relationship between probabilistic spatial language use and speakers' conceptual knowledge. In these previous studies, the authors made use of a small set of hypothesized sub-types, culled from various theoretical and experimental sources. Speakers' use of expressions like *in* and *on* showed principled distinctions among sub-types, suggesting an organized underlying conceptual space. However, this preliminary research left open questions about the nature of this conceptual space. The conceptual knowledge I consider in the current studies takes the form of sensitivity to geometric and functional features of spatial relations. Geometric features of were derived from evidence of pre-linguistic knowledge of properties of Containment and Support relations (Baillargeon, 1995; Hespos & Baillargeon, 2001, 2008; Hespos & Spelke, 2004; Casasola, 2005; Casasola et al., 2003). The functional feature of (Locational) Control was adapted from psycholinguistic work on mature speakers' comprehension and processing of the terms *in* and *on* (Garrod et al., 1999). The work presented in this thesis jointly examines the types of conceptual information that mature (Study 1) and child (Study 2) speakers are sensitive to in their use of spatial expressions and the precise nature of the mapping between this conceptual information and use of different types of spatial expressions.

In Study 1, I showed that adults' rate of use of different expression types over a diverse set of Containment and Support relations is predicted by variation in two sets of geometric features – Enclosure and Volume match for Containment, Vertical position and Surface match for Support – along with a functional feature, Locational Control. Different combinations of features predict adults' use of different types of expressions. For expressions like *BE + in(side)/on (top)* greater usage is predicted by high ratings of geometric features (Enclosure for Containment, Vertical position and Surface match for Support) and by ratings of Control – for *BE + in(side),* high Control ratings predict increased use, while for *BE + on (top)*, low Control ratings predict increased use. Lexical verb use was predicted by the opposite weighting of features: low ratings of geometric features (Enclosure and Volume match for Containment, Vertical position and Surface match for Support) combined with low Control ratings for Containment and high Control ratings for Support. Finally, adults use of *BE + preposition* expressions was predicted by the absence of both geometric properties (i.e., low ratings for geometric features) for both Containment and Support, consistent with the idea that adults use this type of expression to encode relational information other than Containment or Support.

In Study 2, I examined feature knowledge, language use, and feature-language relationships in 4- and 6-year-old children. Children's ratings of geometric features – Enclosure and Volume match (Containment), and Vertical position and Surface match (Support) – were strongly correlated with adult ratings from Study 1. Children diverged somewhat from adults in their ratings of Control for both Containment and Support items, showing less variability in Control ratings and a weaker covariance structure between geometric features and Control, relative to adults. Turning to language, children systematically varied in their use of different expression types to encode the set of Containment and Support items. Children's patterns of use for each expression type were also strongly correlated with adult usage patterns from Study 1. Adults and children differed, however, in their frequency of use of different expression types: adults and 4-year-olds use

BE + inside/on top, *BE + in(side)/on (top)* and lexical verbs at different rates for both Containment and Support, while adults and 6-year-olds differed only in their use of *BE +in(side)/on (top)*. This pattern of developmental differences suggests a continuous developmental trajectory, whereby children's spatial expression use becomes consistently more adult-like as they get older.

Although children and adults were similar in aspects of their feature ratings and language use, the relationship between features and expressions differed across ages. Both 4- and 6-year-olds showed adult-like relationships between expression use and geometric feature ratings, but lacked systematic relationships between Control and the use of different expression types. Child feature-language relationships were especially inconsistent for lexical verb expressions and *BE + other preposition* expressions. For lexical verb expressions, children (in particular, 4-year-olds) may lack knowledge of the particular mechanisms that enable Containment and, especially, Support in the absence of strong geometric properties. This immature knowledge might manifest itself in both the expressions that children choose for items with low geometric ratings as well as the Control ratings that children give to these items. In the case of *BE + other prepositions*, it is likely that both children and adults make use of this expression type when encoding something other than Containment or Support (for example, an expression like *is near/beside* might be used to encode proximity and an expression like *is above/below/over/under* might be used to encode position on an axis). Any age differences in feature-language relationships for this expression type might just reflect differences in the consistency with which adults and children choose to encode the same kinds of relational information (outside of Containment or Support).

In Study 3, I examined an alternative source of information – parent input – that children could make use of in cases where they lack understanding of features or feature-language relationships. I collected parents' estimates of child-directed expression use for the same set of Containment and Support items from Studies 1 and 2. When these input estimates were included as predictors in feature-language models, they improved the accuracy of model predictions for 4- and 6-year-olds' use of all of the expression types. Gains were small, but reliable, for expressions like *BE +inside/on top* and *BE + in(side)/on (top)* and were larger for lexical verb expressions and *BE + other prepositions*. For lexical verb expressions, parent input seems to mediate the relationship between features and language in the absence of children's complete understanding of functional or mechanical aspects of Containment and Support relations. This suggests that in cases of late-developing feature knowledge for complex functional features like Control, parent input can serve as scaffolding for children's spatial language acquisition. For *BE + other preposition*, parent input may simply align with situations in which a child is likely to encode a relation other than the (intended) Containment and Support relations.

Significance of work

In addition to using a new approach to measuring spatial language use, outlined above, the thesis diverges from traditional approaches to spatial language in a number of important ways. The work features a large and broad sample of relations and combines two longstanding perspectives on spatial categorization. I take the targeted approach of infant work, which focuses on the spatial properties for a handful of privileged relations, and combine it with sample-based approaches from cross-linguistic and computational work, which measure language use for large sets of relations in the hope of uncovering categorization patterns from language data alone. The result is a novel perspective on spatial language encoding that uses insights from infant studies to hypothesize the origin of systematic variation in language use across a sample of items that extend far beyond the exemplars studied in infant research, and even beyond cross-linguistic and computational approaches. This work has a number of implications for the study of spatial representation, language acquisition, and the semantics of spatial terms, each of which are addressed in turn below.

Implications for spatial representation and spatial language

In this work, I make a number of related claims about the conceptual knowledge underlying the spatial categories of Containment and Support and their linguistic encoding:

First, Containment and Support categories are structured by a small number of geometric and functional features. Geometric features stem from pre-linguistic knowledge of Containment and Support relations. For Containment, these features include Enclosure (of one object by another) and Volume match (the tightness of fit of one object's volume within another). For Support, these features are Vertical position (of one object relative to another) and Surface match (the overlap of one object's surface with another). One additional functional feature, Locational Control (the control of one object's location by another object), is also thought to play a role in structuring both Containment and Support relations. Knowledge of Control depends on understanding complex, sometimes idiosyncratic and unobservable, properties of objects and configurations, such as the functional consequences of certain materials (e.g., thin mesh compared to solid wood), or the relational affordances of certain mechanisms (e.g., suction cups or tape). As such, there is no expectation that knowledge of Control should be available pre-linguistically, or that children will have acquired complete knowledge of this feature by 6 years of age (the oldest age in my sample).

Second, these features apply to spatial relations in gradable ways: an object can be enclosed by another object to a greater or lesser degree, and this enclosure can feature more or less of a match/fit between the object volumes; likewise, an object can be positioned fully or partially higher (in the vertical dimension) relative to another object, and this positioning can include more or less surface contact between the objects. These and other properties make it more or less likely that one object will exert locational control over another so that, when one object is moved, the other object will move with it. The crux of this thesis is that variation in these features, and, in particular, in combinations of these features, is related to variation that arises in speakers' use of different types of expressions for encoding a wide range of Containment and Support relations. This perspective reconciles the fact that we can use the same spatial term for very diverse cases but that some cases are clearly better instances of an expression (e.g., *in* or *on*) than others. That is, having certain geometric and functional properties licenses a given spatial term and having those properties to a greater or lesser degree relates to how "good" a relation is as an instance of a term.

The strength of the relationship between features and expression use also varied across different expressions. Speakers' use of expressions like *BE + inside/on top* is strongly tied to the small set of features, especially to geometric features. This relationship holds for both adult and child language use, suggesting that knowledge of geometric features is in place early. The use of broader expressions like *BE +in/on* shows a less precise relationship to the proposed geometric features (and increasing dependence on functional information) and the use of lexical verb expressions is related to the *absence* of geometric features.

Finally, the use of expressions with *BE + other prepositions* makes clear that, in some cases, speakers prefer to conceptualize an object configuration as some relation other than Containment or Support, and this is evidenced by inconsistent or haphazard relationships between features and language use.

The large and diverse sample of relations tested in this thesis is a strong test case for a feature-based perspective on spatial language, as the items spanned the full range of feature values for the geometric and functional features under consideration. The consistency of adult and child ratings of these features also suggests that these are properties that speakers and, in the case of geometric features, learners are highly sensitive to.

The features identified in this thesis also shed light on the lexical and compositional semantics of prepositions like *in* and *on*. As discussed in Chapter 2, one prediction of this account is that the truth conditional semantics of descriptions with *in* and *on* should depend on a relation being conceptualized such that it possesses certain features to a minimal degree. Modification provides an interesting test case for this idea. Compositionally, modifiers of *in/inside* and *on/on top*, such as *partly, mostly, half-, or somewhat*, should place thresholds on feature values associated with different relations. The precise threshold is predicted to vary with the modifier. This feature-based account also generally predicts that expressions can overlap in the cases they apply to. If two expressions share similar feature combinations, then they should be used for the same cases. However, the other prediction is that some expressions should be better fits to some cases compared to other expressions, and this should be based on the combination of features. Thus, while language use data was used to generate the features, the prediction is that they should still constrain aspects of the semantics of terms like *in* and *on*.

Implications for spatial language acquisition

Studies 2 and 3 present a view of spatial language acquisition in which children show adult-like grasp of some feature-language correspondences, but not others. Specifically, children show principled adult-like relationships between language and geometric features, but not functional features; this is clearest for expressions like *BE + inside/on top* and *BE + in(side)/on (top)* that children use frequently across Containment and Support items compared to, less frequently used, lexical verb expressions. This pattern of adult-like geometric knowledge combined with immature functional knowledge stands in contrast to a possible alternative pattern in which children's language-feature relationships are just noisy for all features and across all expression types. The results suggest that children early knowledge of geometric properties of Containment and Support relations facilitates their use of *in* and *on* (as well as *inside* and *on top*) but that they require knowledge of specific mechanisms and functional properties (e.g., the knowledge that underlies different mechanisms of Control) of these relations in order to extend other expressions like lexical verbs to some relations. Results of Study 3 suggest a targeted role for parent input in resolving these functional feature mappings. Where children show weak feature-language relationships, such as lexical verbs, parent input is an especially strong predictor of a particular child's expression use.

The targeted role for parent input proposed here differs from previous work, which has examined the role of general input characteristics, such as frequency or diversity of parents' expression use, on children's spatial language. Pruden, Levine and Huttenlocher (2011), for example, examined the relationship between parent input and spatial and language development at 24 months of age and later spatial knowledge and language use at

54 months. They focused on words that encoded (non-relational) spatial characteristics of objects, such as “triangle”, “curvy”, and “long”. Where spatial language acquisition is concerned, their results uncovered relationships between parents frequency of use of these words and spatial language development – children whose parents used these spatial terms more frequently were, themselves, more likely to know the same spatial terms, as well as relationships between input diversity and spatial language development – children with parents who used a greater number of different types of expressions were more likely to have a highly developed spatial vocabulary. The approach in this thesis was to measure parent input estimates for exactly the items that children were describing and, as such, the results may not be accurate as general estimates of parents’ input (i.e., how frequently they talk about spatial relations, how diverse their general child-directed spatial language use is, etc.).

In sum, this thesis carefully sheds light on the content and structure of the knowledge that underlies linguistic encoding of diverse Containment and Support relations. I examine spatial language acquisition and its relationship to the development of geometric and functional knowledge of spatial relations in combination with characteristics of the input environment. In future work, I aim to address both the development of the functional knowledge identified here as well as more nuanced relationships between child spatial language and parent input.

Appendix

Appendix Table 1. List of Containment relation items

Soccer ball in net Sandwich in bag Clothing in (mesh) bag Oranges in (mesh) bag	Bear in sleeping bag Bottle in holder Bottle in sleeve/bag Bouquet in paper	Spoon in pudding Plant in basket Eggs in basket Cake in dish	Golden egg in basket Strawberries in basket Apples in bowl Books in box
Berries in bag Cake in (glass) case Ball in (glass) case Ball in (wood) sculpture	Duck in basket Chocolates in box Shoes in box Flowers in fishbowl	Ice cream in dish Bouquet in vase Bottle in gift bag Towels piled in basket	Tree in basket Flowers in jug Corn in basket Spade in pot
Feather in (glass) ball Toy in (wire) ball Hamster in (plastic) ball Bird in (wire) cage	Onions in basket Plants in fishbowl Towels in basket Juice in glass	Book in holder Newspaper in holder Magazine in rack Magazine in holder	Dart in dartboard Pencil in sharpener Plug in outlet Arrow in target
Trophy in (glass) case Butterflies in mesh cont Bone in (glass) dome Ball in (wood) cylinder	Apple in basket Stones in dish Eggs in basket Peach in bowl	Cork in corkscrew Bolt in nut Bulb in light socket Key in lock	Coin in wrench Sushi in chopsticks Berry in tongs Ice cub in tongs

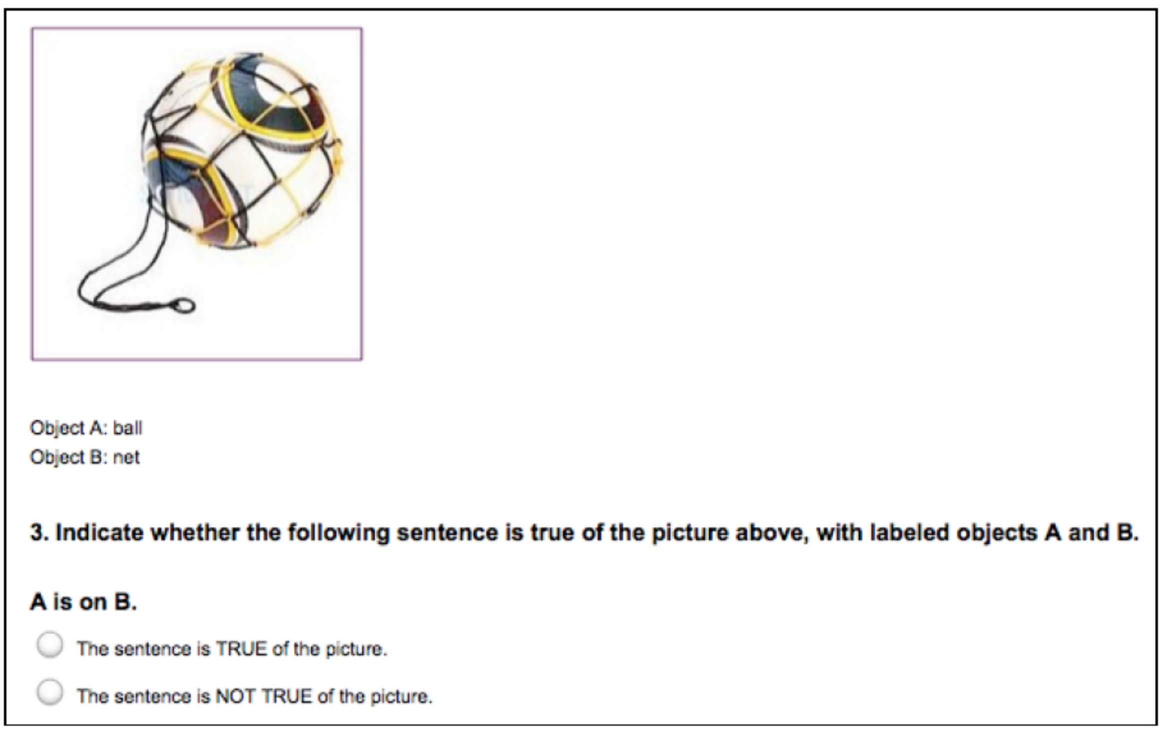
Appendix Table 2. List of Support relation items

Crown on pillow Sandwich on plate Book on book Dishes on tray	Note on fridge door Sticker on window Label on jar Paper on wall	Snail on leaf Butterfly on flower Ice cream on cone Honey on stick	Snail on leaf underside Lizard on ceiling/wall Insect on grass Icicle on roof ledge
Paper on stand Pillow on stool Globe on stand Suitcase on table	Blanket on chair Tarp on tent Cloth on table Netting on bed	Towels on rack Book on stand Dress on hanger Saddle on fence	Light on ceiling Bat on branch Sign on holder Spider on stick
Marble on rod Ball on ball(s) Ball on dome Red block on blue block	Post-it on wall Suction cup on glass Sign on fence Vases on glass	Towel on hook Horseshoe on hook Coat on chair Necklace on stand	Planes on ceiling fan Planets on rods Lamp on chains Puppet on sticks
Plate on rod Egg on pencil Stone on stone(s) Golf ball on golf ball(s)	Banner on sticks Garland on banister T-shirts on clothesline Grapes on vine	Note on wall Sign on hook Mirror on peg Bicycle on shelf	Ornament on branch Pinata on branch Fish on rod Star on hook

Experiment 9: Adult truth value judgments for *BE + in/on*

Method.

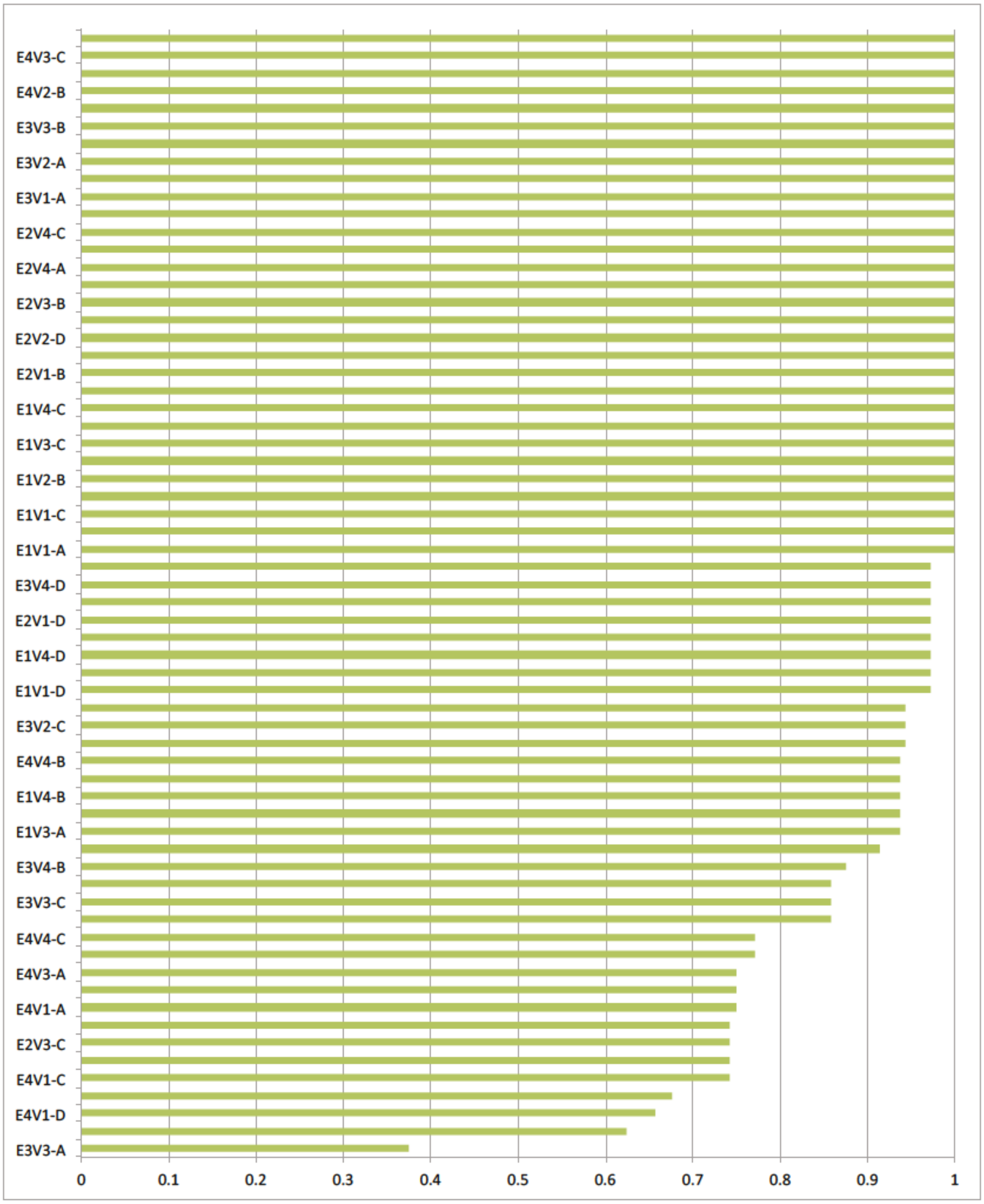
Eighty English-speaking adults participated in the study through an online web interface. Participants were given a self-paced judgment task featuring all 64 Containment and 64 Support items. An additional 22 items depicting proximity relations were included as fillers, yielding judgments on 150 items in total. On each trial, participants were presented with an item with labeled objects and a target sentence and were asked to indicate whether the sentence was true of the item (Figure A-1). Trials were randomized and counterbalanced to ensure an equal number of expected true/false judgments.



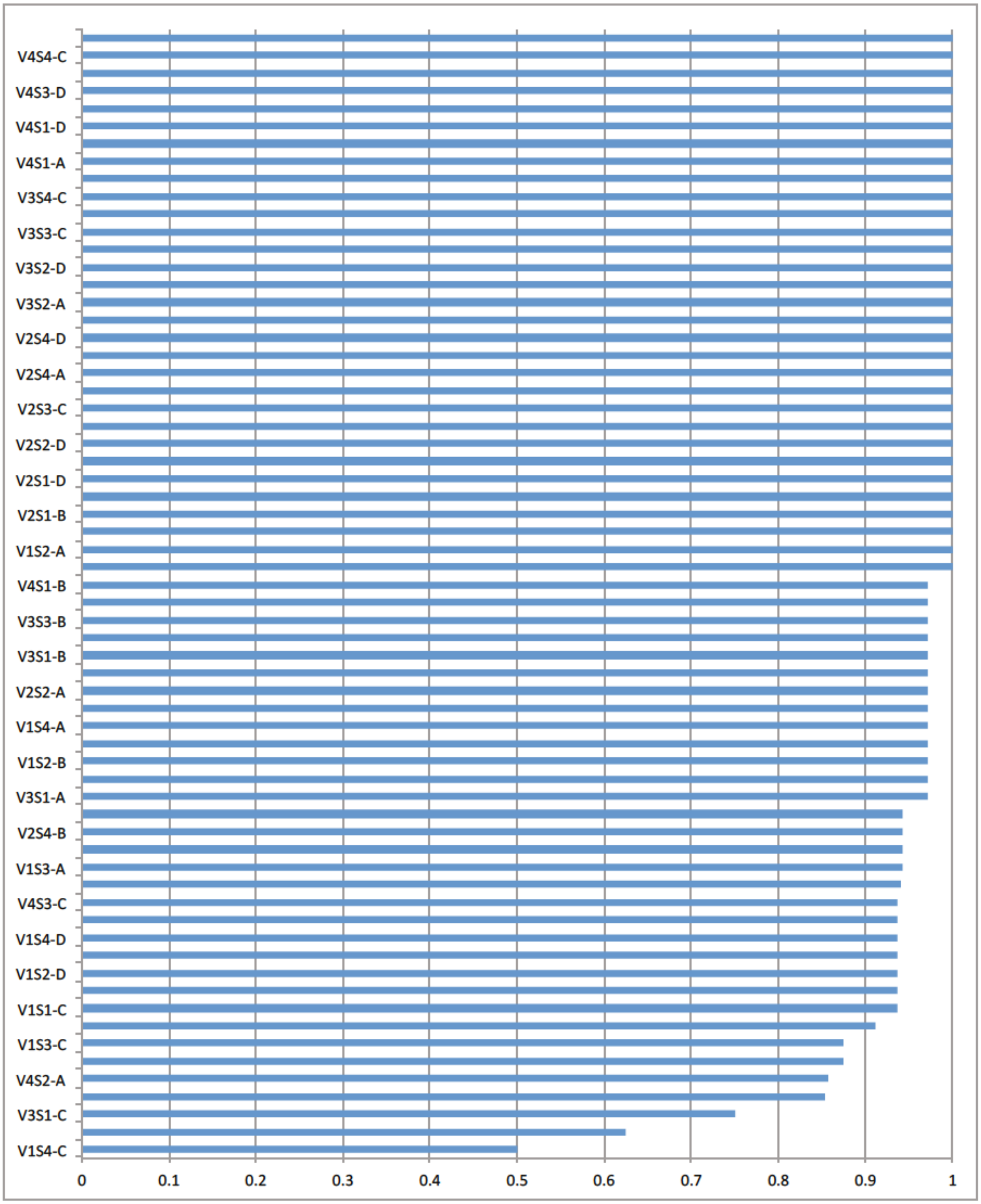
Appendix Figure 1. Example trial for the online truth value judgment task.

Results and Discussion.

Participants' truth value judgments for target *BE + in/on* expressions were close to ceiling: responses almost always accorded with the predicted truth values for Containment (Figure A-2) and Support (Figure A-3) items. There were only 3 Containment items and 2 Support items for which participants chose the expected (i.e., "true") response for less than 75% of items. This uniformity in judgments stands in contrast to the variation found in production (Study 1). Due to the lack of variation in these responses, patterns of truth value judgments were not correlated with the rate at which *BE + in/on* was used to encode these items (r = 0.09; *ns*). Thus, production of these expressions reflects more fine-grained differences between items then the simple truth-conditional semantics of *BE + in/on* would lead one to expect.



Appendix Figure 2. The distribution of truth value judgments for *BE + in* for Containment items.



Appendix Figure 3. The distribution of truth value judgments for *BE + on* for Support items.

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